Crop Response in Salt-Affected Soils

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ABSTRACT. Salt-affected soils, those on which plant growth is limited by an excess of salts, are of three types: (i) saline soils in which electrical conductivity is > 4 dSm^{-1}; (ii) sodic soils in which the exchangeable sodium percentage (ESP) is > 15; and (iii) saline-sodic in which the electrical conductivity (EC) is > 4 dSm^{-1} and ESP is > 15. Salt-affected soils are most common in aridic moisture regimes, and secondary salinization

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(due to anthropogenic activities such as irrigation) may occur by improper management of irrigation. Estimates of the area of salt-affected soils vary widely, ranging from 6% to 10% of earth's land area, and 77 million hectares (Mha) of irrigated lands. Crop yields are drastically affected due to lack of availability of water, nutrients, and oxygen in the root zone. The magnitude of yield reduction depends on the crop, soil type, and management. The reduction in yield normally ranges from 10% to 90% for wheat, 30% to 50% for rice, 50% to 75% for cotton, and 30% to 90% for sugarcane. Crop yield can be enhanced by nutrient management (especially N), water management (irrigation with good quality water and appropriate drainage), use of soil amendments (manures and gypsum, etc.), and use of salt-tolerant varieties.

KEYWORDS. Cotton, irrigation, rice, saline soils, salinization, sodic soils, sugarcane, wheat

INTRODUCTION

Salt-affected soils can be defined as soils on which the growth of most crop plants is limited by an excess of easily soluble salts. Salts are considered easily soluble when they are more soluble than gypsum ($CaSO_4 \cdot 2H_2O$) in water. Salts may include chlorides, sulphates, carbonates and bicarbonates of sodium, potassium, magnesium, and calcium. The diverse ionic composition of salt-affected soils results in a wide range of physiochemical properties. The salt concentration in the soil solution is usually measured by the electrical conductivity (EC) of the soil saturation extract. According to a standard definition, a soil is saline if the EC of the soil solution is greater than 4 dSm^{-1} (SSSA, 1997). However, plant growth may be severely affected or completely hindered at much lower levels of EC.

The Terminology Committee of the Soil Science Society of America proposed to lower the boundary level of EC between saline and non-saline soils to 2 dSm^{-1} (Bohn et al., 1985), but the traditional limit of 4 dSm^{-1} is still in use, with the reminder that sensitive plants are affected already at 2 dSm^{-1} and highly tolerant ones only at higher levels (Soil Survey Division Staff, 1999). The critical EC value for crop reduction may vary over time for the same crop at the same site (Abdel-Ghany et al., 1996), because many factors affect yield, especially at relatively low salinity levels. This critical value of EC changes with the ionic composition of the soil solution and with the salt-tolerance of the plant species and variety growing on the soil. Sodic soils are included in the following discussion, although the EC may be relatively low. The traditional limit of 4 dSm^{-1} still applies to the definition of saline-sodic soils where growth is hindered by the combination of high alkalinity, high Na, and high salt concentration. In the case of saline-sodic and sodic soils, the standard definition requires the measurement of the exchangeable Na percentage (ESP) or the Na adsorption ratio (SAR) in addition to the EC (SSSA, 1997).

In sodic soils, the high Na content relative to other cations is the main factor affecting the productivity of the soil. The critical level of ESP for crop reduction depends on many interacting factors. In Australia, soils are considered sodic if their ESP is $> 6\%$ instead of $> 15\%$, standard from the US Salinity Laboratory Staff (1954). The lower limit is related to low concentrations of soluble salts, low content of calcium, and widespread structural deterioration of Australian soils (Rengasamy and Olsson, 1991). Saline and sodic conditions are very different but often concur in hindering plant growth and development. Consequently, terms such as salinity, saline, and salinization are generically used to refer to both salt and Na stresses (Läuchli and Epstein, 1990). There is a continuum of plant responses to the continuum increase of salt stress with increasing salt or Na concentrations in the soil.

The objective of this report is to synthesize the available literature and estimate yield losses for some major crops grown in salt-affected soils around the world. In particular, wheat (*Triticum aestivum*) and rice (*Oryza sativa*) were studied as examples of staple food crops, and cotton (*Gossipium hirsutum*) as an example of fiber crop. Sugarcane (*Saccharum officinarum*) was chosen as a fundamental source of food, energy and subsistence for tropical regions severely threatened by secondary salinization.

SALT EFFECTS ON PLANT GROWTH AND DEVELOPMENT

Crop yield reductions in salt-affected soils result primarily from alteration of various metabolic processes in plants under salt stress. Negative effects of excess of salts in the soil solution include increased osmotic pressure limiting water uptake (physiological drought), abnormal pH, and ionic competition limiting nutrient uptake (Meiri, 1984; Letey et al., 1990). Salt stresses are always ion-specific, because they change with ionic composition although usually slightly. Specific ion toxicity (Na in particular) has been demonstrated in woody plants, and in herbaceous crops, such as wheat (Läuchli and Epstein, 1990). The literature often does not distinguish between the effects of concentration and of ionic composition. The negative response of plants to low water potential may prevail in saline soils, while single ion toxicity or nutritional unbalance may be particularly severe in sodic soils. Alterations of chemical equilibria and loss of soil fertility are concomitant to structural degradation especially in absence of sufficient Ca^{++}. Soil structural impedance of plant growth may be due to crusting, formation of compacted layers, poor infiltration, and poor permeability to water and air.

Plants differ in their adaptation to the chemical environment and physical structure of the soil. Knowledge of the physiological mechanisms of salt tolerance is important for the genetic improvement of crops grown on salt-affected soils. Plants can be grouped into halophytes (e.g., coconut palm *Cocos nucifera* L., date palm *Phoenix dactilifera* L., and sugar beet *Beta vulgaris* L.) and glycophytes depending on their capacity to transport NaCl into their vacuoles (Shannon and Noble, 1990; Läuchli and Epstein, 1990). Most cultivated plants are glycophytes with limited compartmentation of NaCl. Glycophytes are not as effective as halophytes in ionic partitioning at the cellular level, but more effective at the plant and tissue level (Läuchli and Epstein, 1990). The energy requirement for salt exclusion in glycophytes explains in part the stimulation of root respiration by soil salinity (salt respiration) and the loss of net synthesis of organic C (Lambers et al., 1998). Salt exclusion from the plant may contribute to rapidly rising the salt concentrations in the rhizosphere, already water-depleted, further reducing the soil water potential (Barreto and Valdivia, 1979). Active compartmentation of excess ions in the vacuoles protects salt-tolerant plants from toxicity effect of some ions. However, halophytes and xerophytes growing in highly saline soils are subjected to accumulation of excessive inorganic ions in cell walls, where water from the xylary sap evaporates into the mesophyll. Periodic leaf abscission and active excretion of the salt excess by salt glands on leaf surfaces are mechanisms of salt-tolerance not present in most crop plants (Nobel, 1999).

A metabolic adaptation to low water potentials is increased cell osmotic pressure, which can be achieved through the accumulation in the cytoplasm of osmotic compatible solutes, such as sorbitol, mannitol, and proline (Lambers et al., 1998). Osmolytes in halophytes include uptaken ions so that halophytes need to divert less energy to the production of osmotic compatible solutes (Läuchli and Epstein, 1990). However, in all plants growing on saline media, a part of the metabolic energy is diverted to ion transport, synthesis of organic osmolytes, and ion compartmentation (Läuchli and Epstein, 1990). Osmotic adjustments in salt-tolerant plants need to follow seasonal changes in soil salinity and water availability. Elastic properties of cell walls and variations in stomatal conductance contribute to turgor maintenance and to plant tolerance to salinity (Ball and Sobrado, 1999).

In general, plants that are more salt-tolerant tend to grow more slowly at low salinity levels than less salt-tolerant plants. Broadly adaptable crop plants can produce good yields where strong temporal changes of soil salinity occur in the soil. But, such plants, which tolerate a wide range of salinities, may perform less efficiently at any salinity than less adaptable plants at their optimal salinity. Salt-tolerant plants tend to produce less than sensitive plants because of: (1) greater allocation of organic C in the roots of tolerant plants at the expense of leaf area; (2) decreased use of solar radiation; and (3) low transpiration rate. Adaptation to soil salinity is, in part, a reduction in the capacity for photosynthetic carbon assimilation consequent to the necessity of minimizing evapotranspiration. The efficiency of photosynthetic pigments and nitrate reductase may decrease (Lal, 1996). The effects of soil salinity may interact with those related to climate and other edaphic factors in determining plant growth and development. Reduced availability of water in the soil is concomitant to higher evaporative demand in the leaves. The accumulation of compatible low molecular-weight compounds for osmotic adjustment may be in part related to their alternative function of protection from photo-oxidative damage. On the other hand, the diversion of nitrogen to form organic osmolytes is likely to increase the effect of salinity-dependent nutrient deficiencies and further decrease photosynthesis and growth (Ball and Sobrado, 1999). At low fertility levels, plants may appear more tolerant to salinity than at high fertility levels, if salinity is not the limiting factor of yield (Maas and Hoffman, 1977). On the other hand, nutrient deficiencies induced by salinity and sodicity can further reduce crop yields due to low soil fertility (Bernstein, 1964; 1974).

SALINIZATION

Pedogenetic processes specific to salt-affected soils are salinization and sodication.

Soil Salinization: This is the accumulation of soluble salts in the soil (Bockheim and Gennadiyev, 2000). Environmental factors favorable to salinization are arid and semiarid climates with evapotranspiration volumes greater than precipitation amounts for at least part of the year (aridic, ustic or xeric soil water regimes), saline parent materials, and topographic positions such as closed basins, toeslopes, lowlands, depressions, low lying coasts and tidal areas. The process of salinization may lead to the formation of a salic soil horizon (SSSA, 1997). Often the term salinization is used to indicate a process of secondary salinization, consequent to human use on the land. Secondary salinization is one form of anthrosolization, i.e., pedogenic processes where human activities are the major soil forming factors. Secondary salinization is often consequent to improper irrigation practices. Irrigation is often used in climates where the rates of evapotranspiration exceed precipitation, which also favor salt accumulation. High concentration of salt in the irrigation water and/or improper drainage of irrigated fields are especially hazardous. Irrigation water usually is more saline than rainwater and evapotranspiration tends to further concentrate salts in the soil solution. Even with good drainage the soil solution is on the average 3-4 times more saline than the irrigation water and without proper drainage > 10-20 times more saline (Bernstein, 1974). Improper land leveling is favorable to the formation of salt-affected spots, because salts often accumulate in low-lying areas where the water table (WT) comes close to the surface. In the soil above saline WT, capillary rise of saline water tends to concentrate salts. If the WT is high, soluble salts are concentrated at shallow depths. Consequently, salinization is favored by the rise of saline WTs. Water logging may enhance the negative effects of salinity hindering plant growth by poor soil aeration (Mesa et al., 1979). Compaction may or may not favor capillary rise and upward salt movement (FAO-AGL, 2000).

Excessive use of groundwater in coastal regions or closed basins may cause intrusion of seawater or fossil saline groundwater into non-saline groundwater reserves and subsequent soil salinization (Oldeman et al., 1991). Any agricultural practice leading to increased evapotranspiration in soils with saline parent materials or saline groundwater may contribute to secondary salinization. Deforestation and introduction of shallow-rooted vegetation or fallow practices may change the water balance and cause the WT to rise, and/or form saline seeps (Worchester et al., 1979). Disposal of industrial wastes, excessive fertilization, and use of saline brines may lead to salinization in areas of high population (Bohn et al., 1985). In Thailand salinization is in large part related to large-scale shrimp culture with saline water on arable lands (FAO-AGL, 2000).

Sodication: This is the term used by the Soil Science Society of America (1997) for pedogenic processes increasing the exchangeable Na^+ content of the soil. Salt precipitation depends on the relative solubility of the ionic species present in soil solution. The most soluble ions stay in solution at high concentrations. Ions with higher solubility are moved closer to the soil surface than less soluble ions, when the upward movement of water in the soil prevails. Saline soils may show stratified deposition of different salts in different layers. Sodium forms the most soluble salts that stay longer in solution with decreasing soil water. Less soluble salts precipitate at deeper depth in the profile than Na salts. Sodium concentration increases in the soil solution and Na^+ becomes the dominant cation.

Sodication comprises solonization and solodization processes. Solonization is the pedogenic process of alkalinization, taking place in saline soils. When the excess of salts is leached out and Na^+ becomes the dominant cation (Bockheim and Gennadiyev, 2000), the condition is termed solodization. Solonization occurs prior to solodization consisting of argilluviation of dispersed clay into a natric horizon. Sodication may be a natural process in the presence of Na^+-rich sedimentary materials (e.g., Na-evaporites or Na-rich glacial till), or rocks that can weather releasing Na^+. Sodication may occur when saline groundwater moves toward the soil surface by capillary rise over a high WT, by lateral flow seeping out or by artesian flow. Poor drainage is a major factor of the genesis of sodic soils both in natural and artificial conditions. Desalinization in absence of enough divalent cations is the major cause of secondary solonization and solodization that occur in human-degraded sodic soils (FAO-AGL, 2000).

TYPES OF SALT-AFFECTED SOILS

Most types of soils can be affected by salinity and/or sodicity problems. For agronomic purposes of soil management, at least the simple distinction between saline, saline-sodic and sodic soils is useful. For practical purposes it is important to classify sodic soils according to their pH, distinguishing acidic sodic (pH < 6), neutral sodic (pH 6-8) and alkaline sodic soils (pH > 8) (Rengasamy and Olsson, 1991). The great majority (> 85%) of sodic soils are alkaline, and their reclamation presents the greatest problems (Rengasamy, 1998; Ham et al., 1997).

In the World Reference Base for Soil Resources (FAO-ISIRIC-ISSS, 1998) saline soils are classified as Solonchaks, whereas solodized soils are grouped in the soil group of Solonetz. Solonchaks have a salic diagnostic horizon, and Solonetz have a natric diagnostic horizon. Salt and/or Na^+ accumulation may occur in most soil groups. Qualifiers for naming soil units and sub-units enable the pedologist to provide evidence of the accumulation of soluble salts and/or exchangeable Na^+ when not all the requirements for salic or natric horizons are met. Each qualifier in the World Reference Base for Soil Resources has a unique definition (FAO, 1998).

Flexibility in this system is given by the use of prefixes (Rogel et al., 2001). Names that can be used include Salic, Petrosalic, Endosalic, Episalic, Hyposalic, Hypersalic, Natric, Sodic, Endosodic and Hyposodic. For example, the soil sub-unit Natric indicates the presence of a natric horizon within 1-m from the surface (intergrade with Solonetz group), Sodic indicates that the ESP is > 15 within 50 cm from the soil surface, whereas Hyposodic indicates an ESP > 6.

In Soil Taxonomy (Soil Survey Staff, 1999) soils formed under a warm, arid climate, and having a salic horizon with its upper boundary within 1-m from the soil surface are classified as Aridisols in the suborder of Salids. All other salt-affected soils are scattered in different taxonomic subcategories of the majority of orders. Formative elements used in the nomenclature of salt-affected soils in Soil Taxonomy are Sal-, Hal-, Natr-, and Sodic (Soil Survey Staff, 1998). For example, saline soils constitute the Halic great group of Halaquepts of Inceptisols, Halic subgroups of Vertisols (e.g., Halic Haplusterts), and Salic great groups of Aridisols and Vertisols (e.g., Salaquerts). A natric horizon characterizes Natric great groups of Alfisols, Aridisols, Mollisols and Vertisols. Natric and Salic subgroups of Gelisols are well represented in Antarctica (Bockheim, 1997). Sodic is used at the subgroup level in Aridisols, Entisols, Inceptisols and Vertisols. In Soil Taxonomy, specific requirements for applying a formative element to a soil are adapted to the other prominent features of that soil. For example, a Vermaquept is classified as Sodic if it has an ESP $\geq$ 7 (SAR $\geq$ 6) within 1-m from the soil surface, whereas a Haplocalcid needs an ESP $\geq$ 15 (SAR $\geq$ 13) to be Sodic. The flexibility of Soil Taxonomy suitable for showing different features of salt-affected soils at various taxonomic levels within diverse soil orders is considered an asset (Gupta and Abrol, 1990).

Secondary salinization and sodication may occur in Anthrosols (FAO-ISIRIC-ISSS, 1998) and in diverse orders of Soil Taxonomy (Soil Survey Staff, 1999). Organic soils (Histosols) can be salt-affected (e.g., Halic Haplosaprists), and they are recognized both in Soil Taxonomy (Soil Survey Staff, 1999) and in the World Reference Base for Soil Resources (FAO-ISIRIC-ISSS, 1998).

All considered, salt-affected soils present a broad diversity of hydrological, physical, chemical and biological properties, with textures ranging from heavy clays to sands. Salt-affected soils show peculiar structural features that affect the soil behavior more than the inherent particle size distribution. For example, dunes of saline pseudo-sand may form from saline clays exposed to strong winds (Driessen and Dudal, 1991). The wide range of properties of salt-affected soils needs to be taken into account in the evaluation of experimental results on yield losses caused by salinity or sodicity.

EXTENT AND DISTRIBUTION OF SALT-AFFECTED SOILS

Salt-affected soils are most common in aridic moisture regimes but they may be present at any latitude and altitude (Szabolcs, 1998). Secondary salinization by improper irrigation management was a major cause of degradation of the Nile Delta, the Mesopotamian Plain, and the valleys of the Yangtze and the Hwang Ho (Dregne et al., 1996). Salinization of the Yellow River irrigated plains was limiting cereal production more than 2000 years ago in China (Dregne et al., 1996).

Solonchaks and Solonetz occupy > 322 million ha (Mha) (FAO-ISIRIC-ISSS, 1998). However, salt-affected soils cover a much larger surface. Estimates of the extent of soil salinity and sodicity problems on the earth surface vary from 5% to 10% of the total land area. Szabolcs (1998) reported that salt-affected soils cover about 10% of the lands. Recent estimates of FAO-AGL (2000) indicate that > 800 Mha are salt-affected (i.e., > 6% of the world land area). Salinization affects about 70 Mha of irrigated lands, i.e., one third of the world irrigated area (Bohn et al., 1985). In the USA, 5 Mha of salt-affected irrigated land are reported, mainly in the West (Bohn et al., 1985). The World Map of the status of Human-Induced Soil Degradation indicates that about 77 Mha are affected by secondary salinization (Oldeman et al., 1991). Human-induced salinization affects 45 Mha of irrigated land and 32 Mha of rainfed agricultural land (FAO-AGL, 2000).

Salt-affected soils not currently used for crop production (e.g., salt flats) are a potential source of salts for salinization of surrounding fields (Oldeman et al., 1991). Salinity problems also affect greenhouse crops, mine spoils, and disposal areas. According to estimates of the USDA, about 30% of the land in the USA has a moderate to severe potential for soil salinity problems (Tanji, 1990). Over 33 Mha of the land in the USA and Canada is geologically susceptible to develop saline seeps (Worchester et al., 1979), and salinization by saline seeps has already affected > 0.8 Mha of cropland in the northern Great Plains (Miller et al., 1981). Oldeman et al. (1991) indicated 1.5 Mha as annual rate of loss of agricultural world land by salinization, alkalinization and waterlogging. Previous estimates reported 10 Mha of agricultural land loss per year based on FAO and UNESCO data (World Commission on Environment and Development, 1987). Annual and spatial variations of the rate of increase are likely to occur with maximum expansion of salt-affected soils occurring where land and water resources are poor and the human population is dense.

Yield losses are particularly detrimental at a local scale because salt-affected soils are not uniformly distributed and threaten the continued existence of agriculture in some regions and countries. In Bangladesh 24% of the total land area is salt-affected with a rapid expansion during the last quarter of the 20th century from < 1 Mha to > 3 Mha (FAO-AGL, 2000). In Pakistan 26% of the 16 Mha of irrigated land is affected by salinity. In Hungary 25% of the land is salt-affected and 22% is affected in Argentina (FAO-AGL, 2000). In China 30% of the irrigated and 21% of the rainfed arid lands are salinized (Dregne et al., 1996). Severe yield losses can occur on irrigated lands otherwise highly productive. California produces a large part (e.g., one quarter in 1987) of the agricultural production of the USA and 29% of California's land (i.e., 1.2 Mha of cropland, or 50% of its irrigated land) has sodicity and salinity problems concentrated in the San Joaquin Valley (Hedlund et al., 1990). In Egypt 60% of the cultivated lands of the Northern Delta are salt-affected (FAO-AGL, 2000). The majority of saline soils of Mexico occur in cultivated areas. In the irrigation district of Ciudad Juarez Valley in Mexico the productivity of 70% of the land is hindered by salinity. On the average 25% of irrigated Mexican lands are salt-affected (FAO-AGL, 2000). In China all irrigated areas along the Yellow River from the Ningxia Plain to the Bohai Sea are salt-affected. In addition all the irrigated oases in the dry regions of central and western China suffer from salinity (Dregne et al., 1996), and yields of irrigated rice, wheat and corn (*Zea mays*) are affected by salinity (Huang and Rozelle, 1995).

Twenty-two countries are members of the FAO-UNEP cooperative project established in the Network on Integrated Soil Management for Sustainable Use of Salt-affected Soils. In addition, eight other associated members are running national programs on Management of Salt-affected soils, including Australia and Canada. In Australia almost 20% of the land is salt-affected (FAO-AGL, 2000), in part due to saline seeps that are causing special problems also in India, Iran, Turkey, North and Latin America (Halvorson, 1990).

Changes in the global environment are likely to increase yield losses consequent to soil salinity. The predicted increase of the sea level from thermal expansion of seawater ranges from 15 cm to > 50 cm by the year 2100 (Warrick et al., 1996). The rise of seawater is likely to worsen salinity problems from tidal inundation of coastal lands. On the other hand, no evidence suggests that elevated atmospheric CO_2 would increase the level of salinity suitable for plant growth (Ball and Sobrado, 1999). Instead, increased CO_2 is expected to increase plant growth only on non-saline soils, magnifying potential yield losses consequent to soil salinity.

The distribution of saline and sodic soils by continent shows differences in the salt composition of soils of different regions. Sodic soils are often associated with saline soils and scattered all around the world. They are important especially in Ukraine, Russia, Kazakhstan, Hungary, Bulgaria, Romania, Australia, China, USA, Canada, and South Africa (FAO-AGL, 2000). On a continental scale sodic soils appeared to prevail over saline soils in North America (sodic-saline area ratio = 1-3), Australia (sodic-saline area ratio > 5) and in Europe (sodic-saline area ratio > 10) (Rengasamy and Olsson, 1991; FAO-AGL, 2000).

YIELD AND CROP SALT-TOLERANCE

Crop tolerance is defined in relation to the level of root zone salinity causing yield losses. The term crop resistance is suggested to distinguish glycophyte ability to endure salinity from the tolerance of halophytes (Flowers and Yeo, 1997), but resistance refers to active opposition to biotic stresses according to other definitions (Shannon and Noble, 1990). In practice it is most common to talk of crop tolerance to salinity instead of crop resistance. According to Maas and Hoffman (1977), decreased growth occurs above a soil critical salt concentration (tolerance threshold), usually indicated by a value of electrical conductivity of the saturation extract of the soil at 25°C, or by the exchangeable Na^+ content in the soil. Soil salinity and sodicity limit the potential area of growth of sensitive crops. High salt concentration may lead to plant death and no yield. All plants are sensitive to salts at some concentration. The limiting concentrations change with plant species, variety and stage of development, and duration of the salt stress. Although environmental factors other than high salt concentration may contribute to limit plant growth and yield, the choice of the crop must take into account the specific crop tolerance to salinity in order to avoid total crop failure. Temporal changes of salt-related properties can be rapid and need to be considered when crop planning. Plant response is determined by the time-integrated "effective soil salinity," i.e., the salinity range of the soil solution in the root zone, varying with time and depth during the growing season (Bernstein, 1974). Growth can be inhibited at any stage of the biological cycle. Severe reductions of yields can be due to low germination and limited early plant establishment. Yield reductions can be caused by reduced vegetative growth and/or by perturbation of the reproductive phases (El Falaky and Rady, 1993). Developmental shifts of relative salt-tolerance vary with the cultivar and with the environment (Läuchli and Epstein, 1990). Cereal crops are more sensitive in the early growth seedling stages (Maas and Hoffman, 1977). Seed germination sensitivity to soil salts is usually independent of the subsequent plant tolerance. Seeds of halophytes may not be salt-tolerant during germination, while seeds of salt-sensitive plants may germinate well at high salt concentrations (Läuchli and Epstein, 1990). In general, the stage of germination is not particularly salt-sensitive, but germination failures are likely due to salt accumulation in the topsoil at seed depth (Bernstein, 1974). Crop salt tolerance depends on numerous factors including soil drainage and on the method, frequency, quality and quantity of irrigation, which may favor or remove localized salt accumulations. Often salinity occurs in patches within fields causing irregular plant density and growth, with consequent reduction of the harvesting efficiency (Ritzk and Normand, 1966; Spalding, 1983). Small areas in a field can delay planting, and disturb cultivation of the whole field, increasing the cost of the production (Spalding, 1983). Salt indices calculated on the mean salinity for entire fields are useful if they include the standard deviation of repeated measures of salinity (Rhoades, 1990). Principal soil constraints to plant growth in salt-affected soils are water and nutrient stresses and anaerobiosis.

In general, crops are less sensitive to salinity in glasshouse conditions than outdoors, where wind, low relative humidity and extreme temperatures may increase evapotranspiration. Salinity affects the quality of the production similarly to water stress for many aspects (Bernstein, 1964). Although in some cases the quality of the production might improve (e.g., improved leaf-stem ratio in alfalfa, Maas and Hoffman, 1977), this is not the general rule. Usually increased fertilization and reduction of excessive watering provide better results than soil salinity. Responses to salinity are usually increased fiber and reduced protein synthesis (Joshi and Naik, 1977). Salt accumulation in plant tissues may decrease the palatability of forage crops (Bernstein, 1964) and of potatoes (*Solanum* *tuberosum*) (van den Berg, 1950). Quality changes may decrease the efficiency of processing the produce, including extraction (Lingle et al., 2000) and preservation (van den Berg, 1950).

The US Salinity Laboratory Staff (1954) divided the relative tolerance of crop plants into three classes with high, medium, and low salt tolerance. The effects of salinity on crop yields were indicated with a scale of conductivity with 5 steps of increasing yield restriction (0-2, 2-4, 4-8, 8-16, > 16 dSm^{-1}). At present, a common classification of crop salinity tolerance distinguishes 5 categories. Different limits for tolerance categories have been suggested and individual crops have been classified differently in different publications. A classification of Na^+ tolerance of crops consists of 3 groups, and Na-tolerance tables are usually based on nutritional responses in absence of soil structural degradation (Pearson, 1960), which generally excludes crop production at ESP > 30 (Ayers and Westcot, 1989). A range of values in the continuum of salt and Na stresses may represent the tolerance or sensitivity of a plant better than a single critical value because the intensity of salt stress is not independent of many other factors determining yields (Läuchli and Epstein, 1990).

IMPACT ON CROP YIELDS

Wheat (Triticum aestivum **L.***)*

Francois and Maas (1999) classified wheat as moderately tolerant to soil salinity with a threshold EC of 6.0 dSm^{-1}. Yet the critical value of soil salinity for a decrease in yield equalled 4.2 dSm^{-1} on average in the Nile Delta in Egypt (Abdel-Ghany et al., 1996) and 2 dSm^{-1} in Pakistan (Saeed, 1990). In sodic soils, drastic reductions in yield of wheat occurred at EC less than 4 dSm^{-1} in Na-sensitive cultivars when yields may be reduced to less than a half, from 6.4 to 3.1 Mg ha^{-1}, for ESP increasing from 3% to 45% [yield in Mg/ha = 6.8 − 0.08 ESP, R^2 = 0.99] (Choudhary et al., 1996). In sodic soils, adverse physical conditions are important in limiting wheat yields and, therefore, wheat has been classified as Na-tolerant crop (Pearson, 1960). But, recently specific ion toxicity and nutritional disorders have been evidenced displacing one wheat species to the semi-tolerant on the border to the Na-sensitive class (Ayers and Westcot, 1989; Läuchli and Epstein, 1990). Gupta and Abrol (1990) observed linear decline in yields of wheat and rice (yield of wheat, Mg/ha = $5.88 - 0.06 \times$ ESP, $R^2 = 0.96$; yield of rice, Mg/ha = 6.67 − 0.01 ESP, R^2 = 0.32). Wheat is less tolerant than rice to sodic soils, although for ESP up to 20%, yield of wheat, similar to that of rice, may be unaffected by exchangeable Na content. Abrol and Bhumbla (1979) also reported a linear decline in yield of wheat with an increase in ESP ($y = 4.9 - 0.05$ ESP%, $R^2 = 0.95$).

Vegetative growth of wheat plants on salt-affected soils may decline without evident yield reductions in the presence of controlled irrigation (Bernstein, 1964). However, in field conditions in the absence of optimal water content, at an EC of about 3 dSm^{-1} yields are also depressed, and at an EC of 24 dSm^{-1} plants cannot survive as was reported for 17 cultivars on a Foster fine sandy loam in California (Richards et al., 1987). Other experiments have shown that grain yield may be more affected than straw or total biomass production in hard red spring cultivars (Francois et al., 1994). The relative effects of salt stress on vegetative growth and grain yield vary with cultivar and possibly with the developmental phase at which salt stress occurs. Semi-dwarf wheat 'Northrup King Probred' showed greater reduction of vegetative growth than yield. Grain yield reductions appeared mainly due to reduction of number of spikes and spikelets (Al Abdulsalam et al., 1993; Maas et al., 1996). Poor plant establishment on saline-sodic soils under reclamation may reduce grain yield in the absence of proper seedbed preparation, e.g., ridged rather than leveled (Tiwari et al., 1998).

A linear relationship between wheat yield and soil EC appeared adequate for describing yield reductions of 17 wheat genotypes caused by increasing soil soluble salt concentrations between 5 and 20 dSm^{-1} (average $R^2 = 75\%$; Richards et al., 1987). However, the interaction genotype $\times$ salt concentration can be highly significant and a range of yield reductions per unit increase of soil salinity with different cultivars have been observed. Some of the best yielding cultivars in non-saline soils, such as Anza, Shasta, Yecora Rojo, UC 360, UC 444 and UC44-111, may maintain high yields at high soil salinity (Richards et al., 1987; Francois et al., 1994).

Improvement of tolerance to high sodicity in wheat may take advantage of some characteristics of triticale, which suffers lower yield reductions for increasing ESP, whereas durum wheat (Triticum turgidum L.) appeared more sensitive (Choudhary et al., 1996). Wheat yield reductions were significantly, linearly related to increasing soil ESP in a 6-year experiment ($R^2 = 0.51$, $P \leq 0.003$, $N = 13$) reported by Choudhary et al., (1996).

The critical threshold of soil salinity for yield reductions of spring wheat (0.32% NaCl) appeared lower than that of potatoes (0.42% NaCl) in years with normal climate in the Netherlands, but it may be much higher (0.83% vs. 0.31% NaCl) in cool and wet years (van den Berg, 1950). These results are in agreement with data previously recorded for the Great Plains, where a survey of saline soils in Oklahoma with various textures ranging from sandy loam to clay suggested that for good wheat yield the soluble salt content had to be < 0.5% and for high yields < 0.4% (Murphy, 1934).

Rainfed wheat is subjected to the positive interaction of soil salinity with drought stress causing greater reduction of yield in saline soils as compared to non-saline soils during dry seasons (Bole and Wells, 1979). Salt tolerance and drought tolerance may not be linked, and drought tolerance loses importance in irrigated wheat (Bole and Wells, 1979). However, most often water is of poor quality and scarce where irrigation is practiced, and yields of irrigated wheat are subjected to the combined effects of soil salinity, water salinity, and water amounts applied. Maximum water salinity levels for irrigating wheat are a function of the amounts applied, both contributing to the variation of soil salinity during the growing season (Datta et al., 1998).

Irrigation of wheat with saline water may be possible, with alternating applications or mixing water of different quality, and with proper measures to prevent salinization. For example, along the Pir Mahal Canal in Pakistan, irrigation with saline water of Inceptisols under high risk of salinization was possible by leaving part of the farmland uncultivated and concentrating inputs on cultivated fields (Ghafoor and Masood, 1999). Even in soils containing 60-70% sand, significant yield reductions occur from the first season in the case of irrigation with pure saline water of EC ≥ 8 dSm^{-1} and yield losses increase with time in parallel to increases of soil salinity (Singh and Narain, 1980). Use of drainage water for irrigating wheat is possible without excessive salt accumulation in the soil in mixture or in turns with non-saline water when drainage is provided, but reduction of yields as compared to irrigation with non-saline water can be expected (Francois et al., 1994; Chang et al., 1998). Vegetative growth and grain yields are both affected (Naresh et al., 1993). Selection for high grain yield of wheat genotypes tolerant to saline irrigation seems more practical than selection for high biomass production (Kelman and Qualset, 1991), since saline water applications tend to decrease more grain yield than straw yield lowering the harvest index (Al-Abdulsalam et al., 1993). Saline irrigation may also affect wheat quality increasing the grain protein content (Al-Abdulsalam et al., 1993).

Differences in wheat yields between mixed or alternate saline water applications have been shown non-significant (Chang et al., 1998). In general, mixing saline and non-saline soils does not seem advantageous as compared to cyclic irrigation for either grain or straw production (Naresh et al., 1993; Sharma et al., 1994). Differences in wheat yield between type of sequences of saline (EC 13 dSm^{-1}, SAR 14) and non-saline (EC 0.4 dSm^{-1}, SAR 0.7) irrigation did not appear significant (Sharma et al., 1994). If there is not a rainy season effective for leaching accumulated salts, a pre-plant heavy irrigation can assure plant establishment in sandy loam or lighter-textured soils (Sharma et al., 1994). Some results from sand tank cultures of wheat in the greenhouse (Maas and Poss, 1989) suggested that application of saline water at different stages of wheat development could differently affect grain yield, with a possible tendency for saline irrigation at early stages to give lower yields than closer to harvest (Naresh et al., 1993). But, in order to obtain good wheat yields, maintaining soil salinity during the growing season below threshold levels was subsequently proved more important than early application of non-saline water. In practice, the average EC during all growth cycle appeared to dominate the final wheat performance as shown for 'Yecora Rojo' and 'Anza' watered with saline water before or after the terminal spikelet differentiation (Francois et al., 1994). Although the linear relationship between yield and soil EC was significant even for EC measured at a single time during the growing season, EC at terminal spikelet differentiation explained only 35% of the variability in wheat yield, and EC at harvest 54%, whereas the average EC during the growing season > 80% (Francois et al., 1994). Irrigation with sodic water may be applied to wheat in well-drained sandy-loam soils if gypsum is added to limit excessive increase of ESP of the soil (Bajwa and Josan, 1989; Bajwa et al., 1993). But despite gypsum addition repeated irrigation with sodic water may increase soil ESP and decrease wheat yield, even though high yields may still be obtained during the first years (Bajwa and Josan, 1989). Gypsum application in the water during irrigation may not be preferable relative to a single dose when the total amount of irrigation water is not sufficient for causing measurable changes in ESP during one growing season (Bajwa and Josan, 1989). However, even in sandy loam soils irrigation with saline water with EC $\geq$ 4 dS m^{-1} and SAR $\geq$ 6 can increase soil salinity and sodicity (Singh and Narain, 1980). Careful water management is usually necessary for preventing the rise of the WT and soil salinization, occurring in the wheat growing irrigation circle of Sirsa in India at rates of 98 mm $year^{-1}$ and 1.81 Mg of salt ha^{-1} y^{-1}, respectively, without clear relationships between rates of salt accumulation and present wheat yields (Bastiaanssen et al., 1999). Lower irrigation requirements of wheat than paddy rice, coupled with a fair Na and salt tolerance, are favorable to wheat introduction in crop rotations during reclamation of salt-affected soils (Gupta and Abrol, 1990). In addition, because of its high water use efficiency, wheat is a potential crop for recharge areas of saline seeps especially where relatively shallow topsoils overlie dense subsoils (Schneider et al., 1980).

Increasing the frequency of irrigation may not alleviate soil salinity or sodicity stress on wheat (Bajwa et al., 1993). On the other hand, yield losses caused by irrigation water salinity can be reduced with N fertilization in sandy-loam soils. Experiments in Saudi Arabia regarding addition of urea at a rate of 200, 250, and 300 kg N ha^{-1} limited wheat yield reductions in plots irrigated with saline water although increased salinity of irrigation water decreased growth and grain production at all N levels (Al-Abdulsalam et al., 1993). A positive effect of N appeared in saline silty-clay soils in Pakistan, giving yields > 4 Mg ha^{-1} at EC of 10 dSm^{-1}, as compared to yields < 2 Mg ha^{-1} at EC of 5 dSm^{-1} in low fertility plots (Saeed, 1990). Addition of N fertilizers may improve wheat performance in saline-sodic and sodic soils in the process of reclamation (Obrejanu and Sandu, 1971; Tiwari et al., 1998). In summary, N fertilization experiments confirmed the prevalent linearity of yield decrease consequent to increasing salinity, and suggested that the unit decrease of yield per unit increase in EC may vary with the fertility level (Al-Abdulsalam et al., 1993).

Positive wheat yield response to phosphogypsum in saline-sodic soils with clay-loamy texture under reclamation was shown in the Romanian Plain, where application of this amendment was able to take the production to levels of close fields on non-saline non-sodic soils (from an average of 3 to 4 Mg ha^{-1}; Sandu and Mihaescu, 1989). Amelioration of sodic soil caused by phosphogypsic treatments appeared long-lasting (Obrejanu and Sandu, 1971). Yield increases follow the improvement of the soil physical and chemical properties for plant growth (Sandu and Mihaescu, 1989). Enhanced crop growth consequent to ameliorative soil treatments enriches the soil organic matter (SOM) content, which in turn contributes to improved soil conditions, and to the positive residual effects of amendments and fertilizers on wheat yields in salt-affected soils (Raikov, 1971). Furthermore, addition of organic amendments to saline-sodic soils during reclamation can produce two or three fold increases of wheat yields as compared to leaching or leaching + gypsum or sulphur alone (Somani and Saxena, 1981). Even residual effects of animal or green manure applications to preceding crops can enhance wheat yields in saline-sodic soils (Tiwari et al., 1998). In the absence of sufficient natural drainage, placement of subsurface drains is required prior to leaching. Closer drain spacing is expected to support maximum wheat yields (Sharma and Singh, 1998). The variation of wheat yields follows the variation in soil salinity and sodicity within artificially drained fields with maximum yields close to drains, where minimum salinity and sodicity are recorded (Sharma and Singh, 1998). Deep ripping can enhance salt movement favoring leaching (Chang et al., 1986). On the contrary mixing of amendments, such as gypsum, may be more successful at shallow depths, probably due to a dilution effect when a larger soil volume is involved (Khosla et al., 1973).

General trends of wheat yield in relation to soil salinity are outlined in Table 1. Genetic improvement of wheat for salt-tolerance has a great potential of acquiring some halophytic traits such as Na and chloride exclusion by crossing cultivars of *Triticum aestivum* L. with genetically related halophytes, such as *Lophopyrum elongatum* (Host) Löve (Omielan et al., 1991). The possibility of improving salt-tolerance by gene transfer of salt stress inducible transcription factors is under study (Yamaguchi-Shinozaki and Shinozaki, 2001). Even in germplasms without strong salt-tolerance, identification of promoters for tolerance genes may be possible with the advantage of preventing constitutive expression of tolerance genes, which can greatly limit growth and productivity, as compared to wild type plants in the absence of stress. Wheat and rice are primary candidates for this way of improving tolerance, although experimentation has just started and field tests are required (Yamaguchi-Shinozaki and Shinozaki, 2001).

Rice (Oryza sativa L.*)*

Paddy rice can suffer yield losses when the electrical conductivity of the irrigation water (assumed equal to the electrical conductivity of the soil) is > 3 dSm^{-1} (Table 2) (Francois and Maas, 1999). At EC > 3 dSm^{-1}

TABLE 1. Wheat yield reductions as a function of different soil salinity and sodicity (coefficient of the linear regression, significant at $P< 0.05$).

Reference	Coefficient (Mg ha^{-1})	Δ Salinity or sodicity	Yield range (Mg ha^{-1})	Salinity or sodicity range
Abrol and Bhumbla (1979)	-0.05	1 ESP	0-4	10-90 ESP
Abrol and Bhumbla (1979)	NS	1 ESP	1-3	5-20 ESP
Bajwa et al. (1993)	-0.03	1 ESP	5-6	3-40 ESP
Francois et al. (1994)	-0.38	1 dSm^{-1}	0.5-6	6-24 dSm^{-1}

TABLE 2. Rice yield reductions as a function of different soil salinity and sodicity (coefficient of the linear regression, significant at P < 0.05).

Reference	Coefficient ($Mg\ ha^{-1}$)	Δ Salinity or sodicity	Yield range ($Mg\ ha^{-1}$)	Salinity or sodicity range
Abrol and Bhumbla (1979)	−0.07	1 ESP	4-7	ESP
Abrol and Bhumbla (1979)	NS	1 dSm^{-1}	7	2-20 dSm^{-1}
El Falaky and Rady (1993)	−2.67	1 dSm^{-1}	1-3	1-13 dSm^{-1}
Asch and Wopereis (2001)	−0.6	1 dSm^{-1}1 flood water	0.3-0.9	0-8 dSm^{-1}
Asch and Wopereis (2001)	−1	1 dSm^{-1} flood water	0.2-0.8	0-8 dSm^{-1}

the rate of yield decrease is high so that rice has been classified as a sensitive crop or most often moderately sensitive to salinity. Rice appears even more sensitive in the early developmental stages after germination. Rice is also sensitive at flowering, whereas at germination stage it is considered exceptionally tolerant (Bernstein, 1964). At germination and during maturation rice exhibits its highest tolerance. However, salt stress in all developmental stages of rice can contribute to yield losses (El-Saidi, 1997). Vegetative growth can be reduced in all parts (roots, leaves, stems, number of tillers, fresh and dry matter), as well as panicle length, number of branches per panicle, and seed number and weight can be reduced.

The field performance of rice shows a wide variation. In Egypt, rice ('Giza 172' in particular) was indicated as highly tolerant to salinity (El Falaky and Rady, 1993). In central Asia, rice has been termed as a 'salt-friendly' crop, grown in alternative to wheat on solonchacks in the process of desalinization (Esenov and Redjepbaev, 1999). In the cropping sequence used for reclamation in the Dashkhovuzsky velajate area of Turkmenistan, rice and wheat precede cotton. Rice with proper drainage and abundant irrigation may be grown for the first 2-3 years during leaching of saline soils provided that enough nutrients are supplied (Esenov and Redjepbaev, 1999). For best results, besides implementation of effective drainage, irrigated forage crops may be grown in rotation with rice during the reclamation process (Abrahám and Boskai, 1971).

Rice is considered moderately tolerant to exchangeable Na (Pearson, 1960; Ayers and Westcot, 1989), even when quite sensitive to salinity (Pearson, 1960). The salt-sensitivity of rice limits the success of rice cropping during leaching of saline soils until enough reduction of salt concentration has been achieved. Yet, the practice of flooding paddy rice is beneficial for salt leaching (Khosla et al., 1973). Therefore, repeated rice cropping cycles have been recommended to progressively remove salinity and sodicity (Obrejanu and Sandu, 1971). Paddy rice can be effectively cropped during reclamation of sodic soils probably because the water on the fields limits the negative effects of degraded soil structure on the plants. In addition, rice shallow root system makes the plant less sensitive to high contents of exchangeable Na in the sub-soil (Abrol and Bhumbla, 1979; Yield, Mg/ha = 7.9 − 0.07 ESP, $R^2 = -0.89$).

The tolerance to sodicity of rice may lead to soil sodication if irrigation is carried out with sodic water. Therefore, in order to maintain long-term soil productivity, rice may be excluded from crop rotations if alkaline water is used for irrigation. Application of sodic waters significantly decreases rice yields even if reductions may be less marked than in other crops, and yields may be still high when sodic waters are amended with gypsum (Bajwa and Josan, 1989). The yield of rice in rotation with wheat or potato decreased from 4 Mg ha^{-1} in 1974-75 to 3 Mg ha^{-1} in 1989-90 at Kanpur, India with use of alkaline water in the absence of gypsum or pyrites as amendment (Gupta and Abrol, 1999). Gypsum added to the irrigation water at each irrigation may be preferable to one dose addition for improving rice yield in the case sodic irrigation because repeated gypsum treatment prevents Na increase during the growing season (Bajwa and Josan, 1989). The depth of mixing applied gypsum determines the effectiveness of gypsum in improving rice yields, which becomes smaller as mixing depth increases (Khosla et al., 1973). Application of phosphogypsum was particularly effective for increasing rice yield during reclamation of saline and sodic soils in Romania (Obrejanu and Sandu, 1971). Manure and various organic amendments can improve rice yield on salt-affected soils similarly to gypsum, as shown in Brazil (Gomes et al., 2000). For the reclamation of saline soils in Turkmenistan, Uzbekistan, Tadjikistan and Kyrguzstan in central Asia growing perennial forages or barley (Hordeum vulgare) was suggested in order to increase SOM and nutrients before planting rice if manure is not available (Esenov and Redjepbaev, 1999). Also in India animal or green manure and N fertilizer appeared favorable to rice cropping in saline-sodic soils under reclamation (Tiwari et al., 1998). In the process of rehabilitation of acid-sulphate saline soils lime applications can double rice yields (Montoroi et al., 1993).

Installation of subsurface drainage may be required to allow leaching, and can significantly increase rice yields on low-lying salt-affected soils such as acid sulphate saline soils. Furthermore, subsurface drainage of rice fields can prevent seasonal salt accumulation due to intrusion of seawater (Mathew et al., 2000). Salinization due to rice cropping without proper drainage was considered the cause of yield losses leading to abandonment of agricultural land use in the Senegal River Delta (Ceuppens and Wopereis, 1999). On the contrary, by monitoring changes in soil salinity in the region, rice crops appeared to alleviate the salinity problem caused by a shallow saline WT naturally present in the Delta. However, the decrease of EC in the topsoil was not enough for profitable rice yields on saline soils in the absence of drainage and rice culture was usually abandoned (Ceuppens and Wopereis, 1999). Abandonment of rice cropping in salinized low-lying waterlogged areas of Sri Lanka has been similarly reported (Wijeratne, 1999). Experiments conducted in the Casamance region of South Senegal showed that construction of anti-salt dams to convert to rice cropping in salinized mangrove coastal areas may not be sufficient without an efficient drainage network that alone can cause 2-3 fold increases of rice yield from the commonly obtained 1 Mg ha^{-1} (Montoroi et al., 1993). The drain spacing should be set at a distance close enough to reduce salinity and sodicity at a level tolerated by rice as shown in recent experiments in coastal saline sodic clay soils in India, where increasing the drain spacing from 15 m to 35 m resulted in an increase in soil EC 1:1 from 3.8 to 9.2 dSm^{-1} and ESP from 25 to 48.7 at 0-15 cm depth and in a decrease of rice yield from 6.5 to 6.9 Mg ha^{-1} (Singh et al., 2000). High WTs did not appear to affect rice yield except in the case of saline groundwater, which can decrease yield by increasing soil salinity through capillary rise above the WT (Cassanova et al., 1999).

Differences in yield response of rice to soil salinity can be related to climatic variations. In particular, a low relative humidity of the air during the growing season can enhance the yield losses per unit increase of salt concentration because the potential yield is higher in the dry season, as a consequence of longer and more intense solar radiation in the dry season than in the wet season (Asch et al., 2000). The effect of dry air may further depress rice yield lowered by soil salinity both in dry and in wet seasons when usually yields tend to be higher than in the dry season on saline soils (Asch and Wopereis, 2001).

Soil salinity may interact with texture in affecting rice yield as appeared in a survey over 50 rice fields in the Ebro Delta in Spain (Cassanova et al., 1999). In that region moderate yields were obtained on soils with high salinity and high clay, and minimum yields on sandy soils in coastal areas, soil salinity and particle size distribution were linearly related to rice yield.

Narrow plant spacing may help to optimize plant population density in saline-sodic soils (Tiwari et al., 1998). In general, using high planting density (e.g., 200,000 instead of 125,000 plants ha^{-1} on mangrove soils in South Senegal) favors high final rice yields in saline conditions (Montoroi et al., 1993).

Proper tillage is particularly necessary for rice cultivation in salt-affected areas. In dry-seeded, delay-flood systems common in the southern USA, increased soluble salt concentration near the soil surface is favored by no-till systems and can be deleterious to stand establishment. Consequently, no-till can cause significant yield reductions (> 1 Mg ha^{-1}) as compared to tillage (Pearce et al., 1999; Wilson et al., 2000). Similar results were obtained for wet-seeding rice with no-till causing too shallow root development of rice and negatively affecting yield on saline soils under reclamation, where plowing followed by roto-till can favor uniform root distribution and high grain production (Lee et al., 1999). Tillage contributes to redistributing soil salts by breaking the salt crust and favoring water infiltration (Montoroi et al., 1993).

Sea flooding can severely depress rice yield in coastal areas. Rice yield loss is caused to a great extent by reduced percentage of ripened grains (Kim et al., 1999). Worse damages occur with deeper sea water levels, higher salt concentration and longer flooding time. Even a few hours of submersion with seawater (≥ 1.5% salt concentration) may kill rice. Rice yields suffer more when flooding occurs at heading stage than at grain filling and least at booting stage (Kim et al., 1999). Frequent exchange of non-saline irrigation water and spraying with non-saline water soon after saline submersion can effectively limit rice yield damages, as shown in Korea after the spring tide (Kim et al., 1999). In Sri Lanka, irrigation of rice with saline water with EC of 1-1.8 dSm^{-1} appeared feasible in soils with < 40% clay without adverse effects on the yield, but irrigation with water with EC of 2.8 dSm^{-1} may cause complete crop failure (Jeganathan and Pain, 1982). Water with EC > 5 dSm^{-1} can be used only for the latest irrigation after flowering. In Vertisols of the West African Sahel, rice yield reductions are expected for floodwater with EC > 2 dSm^{-1} independently of the developmental stage, although special care is advisable to prevent stresses during the early reproductive stages (Asch and Wopereis, 2001). Decreasing the depth of the standing water in the basins from 12.5 cm to < 1 cm did not improve stand establishment or alleviate yield losses due to saline water applications, which increased soil salinity (Jeganathan and Pain, 1982).

Significant differences between cultivars have been observed in rice tolerance to salinity both at vegetative and at reproductive stages. Shorter cycle varieties may perform better than longer cycle varieties in salt-affected soils and/or with saline irrigation (Jeganathan and Pain, 1982). Better plant establishment and vegetative growth do not always support yield since salt-stress at flowering may still cause crop failure (Jeganathan and Pain, 1982). Differences in variety response to salinity are affected by seasonal and annual changes of climatic conditions. Therefore, the decrease of grain yield for unit increase of soil salt concentration differs among cultivars, seasons, and years (Asch et al., 1999). Field screening of cultivars for salt-tolerance is most important during dry seasons when salt stress tend to produce the most severe yield losses (Asch and Wopereis, 2001). During a wet season the negative effects of salinity on yield components (such as grain weight and spikelet fertility) are usually less pronounced (Asch et al., 1999). In field tests in the Philippines anther-culture-derived lines from F1 crosses showed promising results for improving rice yield stability to salt-stresses in a short time (Zapata et al., 1991). The leaf K/Na measured at the vegetative stage may be a convenient index for predicting yield losses of rice in salt-affected soils (Asch et al., 2000).

Cotton (Gossypium hirsutum **L.***)*

A considerable amount of research has been done to assess salt-tolerance of cotton (Table 3). Cotton is one of the most salt tolerant crops as shown by the high performance of the Acala type 'J-2' under irrigation with saline water (EC 8 dSm^{-1}) in the San Joaquin Valley of California (Rhoades et al., 1980). Cotton was outstanding for successful cropping on salt-affected soils already in the 19th century (Hilgard, 1886). Francois and Maas (1999) confirmed the salt-tolerance of cotton and indicated lack of differences in yield among cultivars at salinity levels that allow economic production. However, high genetic variability in the response of cotton to soil salinity and sodicity exists within *Gossypium hirsutum* L. species for different varieties and within *Gossypium* genus for *G. hirsutum* L., *G. barbadense* L. and *G. arboreum* L. (Choudhary et al., 2001). Most data reported in this following section refer to the salt-tolerance of *Gossypium hirsutum*, but some attention is paid also to *G. barbadense* because of its special importance in Egypt and in other arid and semiarid regions where soil salinity may severely affect cotton yields. The intra-specific genetic variation of *Gossypium hirsutum* allows the identification of salt tolerant lines by mass selection in the field just after single selection cycles (Ashraf and Ahmad, 1999; Y, Mg ha^{-1} with drainage = $4.6 - 0.037$ EC, dSm^{-1}, $R^2 = 0.90$; Y, Mg ha^{-1} without drainage = $3.15 - 0.036$ EC, dSm^{-1}, $R^2 = 0.99$).

Area and yield data of cotton and other crops in a salt-affected irrigation district of the San Joaquin Valley, California, followed temporal

TABLE 3. Cotton yield reductions as a function of different soil salinity and sodicity (slopes of the linear regression, significant at $P < 0.05$).

Reference	Δ Yield (kg ha^{-1})	Δ Salinity or sodicity	Yield range (kg/ha)	Salinity or sodicity range (dSm^{-1})	Notes
Russo and Bakker (1987)	−115	1 dSm^{-1}	2800-3600	3.6-10.5	1000 mm irrigation
Russo and Bakker (1987)	−289	1 dSm^{-1}	4000-6000	3.6-10.5	1600 mm irrigation
Russo and Bakker (1987)	−319	1 dSm^{-1}	4200-6400	3.6-10.5	1800 mm irrigation
El Falaky and Rady (1993)	−157.16	1 dSm^{-1}	300-1500	3-13	
Habib et al. (1993)	−110.1	1 dSm^{-1}	700-4100	1-23	Nile Delta
Habib et al. (1993)	−74.7	1 dSm^{-1}	700-2800	3-23	Clay, 0.7 m WT
Habib et al. (1993)	−100.7	1 dSm^{-1}	1800-3900	1-15	Loam, 1.0 m WT
Habib et al. (1993)	−289.6	1 dSm^{-1}	1000-4100	2-11	Clay, 0.9 m WT
Wiegand et al. (1994)	−43	1 dSm^{-1}	0-900	1.5-14	Within salt-affected fields
Choudhary et al. (2001)	−0.12	1 ESP	350-900	3-56	‘F505’
Choudhary et al. (2001)	−0.06	1 ESP	650-900	3-56	‘F846’

variation of soil salinity due to changes in management practices with reduction of cotton crops parallel to reduction of salt problems (Wichelns et al., 1990). Nevertheless, cotton culture had to be abandoned in salinized areas such as the Southwestern Indo-Gangetic Plains. In the Nile Delta, cotton has shown greater sensitivity to soil salinity than rice either because of the cotton species and variety grown (*G. barbadense* 'Giza 72' in particular) or because of the salt ionic composition with dominance of NaCl (El Falaky and Rady, 1993). Cotton usually does not come first in the reclamation of salt-affected soils. It follows fodder and grain crops on solonchacks, formed by secondary salinization in the irrigated lands surrounding Turkmensih oases in the process of reclamation starting with 1-2 years of rice (Redzhepbaev, 1981).

Decline in yield may be caused by reduction of germination, delayed emergence and slow seedling growth (El-Saidi, 1997). Plant density was drastically reduced after two years of irrigation with saline drain water although during the first two years no significant effects of soil salinity were observed on lint yield despite a rise of soil EC at 0-90 cm depth up to 15 dS m^{-1} at the end of the second year (Rains et al., 1987). In other experiments, saline water significantly reduced plant establishment already in the first year of applications (Rhoades et al., 1980). Young cotton seedlings appeared particularly sensitive to soil salinity when, among other ionic species, B is present in excessive amount in the soil solution (Mamani et al., 1998). In general, the most sensitive stage to salinity is flower bud formation, when growth can be completely arrested and high shedding induced. Cotton plants are much more resistant after flowering to salt concentration in the soil (El-Saidi, 1997).

The plant size of cotton may be drastically reduced without yield decline (Bernstein, 1964; Rhoades et al., 1980). Cotton vegetative growth may be initially affected, but then plants may recover (Rains et al., 1987). However, most often decreased vegetative growth is concomitant and likely to contribute to significant quantitative and qualitative yield losses. Stunted and shorter plants with smaller and thicker leaves growing on saline plots may produce lighter and fewer bolls per plant than those grown on non-saline soil. An average yield loss of 1.5 Mg ha^{-1} was recorded at a soil EC of 19 dSm^{-1} in the top 90 cm as compared to the yield of 3.4 Mg ha^{-1} of 'SJ-1' Acala cotton at 1.3 dSm^{-1}, mainly as a consequence of a reduction of boll number (Francois, 1982). The relative effect on cotton yield of decreased boll number and boll mass may change with cotton type, variety, and environment. Other studies indicate yield losses > 2.5 Mg ha^{-1} of cotton lint despite an increased number of bolls per plant as soil soluble salts increase from 0 ppm to 6000 ppm (Soliman et al., 1976). Smaller plants on saline soils do not have enough leaf area to cover the surface. Plant density can be changed according to the local variation of salinity to limit yield losses (Francois, 1982). However, cotton shows good compensation of plant number with plant size, and not always significant positive effects on yield of increasing the number of plants per unit surface was found for soil EC up to 7 dSm^{-1} (Mamani et al., 1998).

Salinity affects cotton yield by inducing early flowering (Soliman et al., 1976), early maturation, and shortening the fruiting period (Longenecker, 1973). But it is not clear if decreased number of late season bolls may contribute to yield losses. In Na-affected soils maturation coefficients may not be affected (Choudary et al., 2001).

Although lint yield of cotton is sensitive to salinity (Y, $Kg\ ha^{-1} = 3231 - 110\ EC\ dSm^{-1}$, $R^2 = 0.57$) the quality of cotton fibers may be only slightly affected by salinity (Bernstein, 1964; Longenecker, 1973; Habib et al., 1993) or sodicity (Choudary et al., 2001). However, salt stress at bud formation may severely reduce not only the quantity of seeds and bolls, but also the quality of cotton fibers, becoming shorter and less fine (Habib et al., 1993; El-Saidi, 1997; Ashraf and Ahmad, 1999). Shorter and less fine cotton fibers may be produced as a direct consequence of water stress at flowering (Heuer and Nadler, 1999), enhanced by saline conditions. In Na-sensitive cultivars decreased fiber span length, and bundle strength were recorded with increasing sodicity (Ashraf and Ahmad, 1999; Choudary et al., 2001). On the other hand, some salt-tolerant lines may produce less fine fiber than salt-tolerant lines grown at the same salinity level (Ashraf and Ahmad, 1999).

Cotton is a Na-tolerant crop, but sensitive in the early stages, suffering more from adverse soil physical conditions than nutritional factors (Pearson, 1960; Ayers and Westcot, 1989). Similar to salinity, sodicity decreases growth especially in the initial stages. Close to maturity differences in growth diminish, but yields decline. Sodicity up to 16 ESP did not reduce cotton yield even in sensitive cultivars such as 'F-505' (Choudary et al., 2001). But higher ESP values may cause a marked yield decline consequent to reduced vegetation, decreased boll number, and boll weights. The yield reductions are mainly due to fewer bolls. Boll weight may not be affected by sodicity in Na-tolerant cultivars, e.g., 'F-846' (Choudary et al., 2001). Although negative and highly significant correlations between SAR in the top 0-25 cm of soil and cotton yield were found in Egyptian soils, soil salinity seem to explain most of the yield variability in the Nile Delta, and no significant correlation between chloride and sulphate anionic ratio and either cotton yield or fiber qualities was observed.

Variation of cotton lint yields from 0 to 900 kg ha^{-1} appeared linearly related to variation of soil salinity within and between salt-affected fields, with a decrease of yield of about 43 kg ha^{-1} per unit increase of EC, with a range of variation of regression coefficients much larger (Wiegand et al., 1994).

The irrigation of cotton with saline water containing up to 8000 ppm of soluble salts may produce acceptable yields in sandy soils, such as sandy coastal soils of Pakistan despite yield reductions with increasing salinity levels (Ahmad and Abdullah, 1982). In the Negev Desert, irrigation with water containing 2300 ppm of soluble salts did not produce significant differences from water with 600 ppm of soluble salts in cotton Acala 'SJ-1' yields during 2 years of experiment. However, significant cotton Acala '1517 D' yield reductions were already observed with less saline water (4000 ppm soluble salts) in Texas, which decreased both seed cotton per boll and number of matured bolls per plant (Longenecker, 1973). Although non-significant yield reductions were recorded using drainage water (EC 3 dSm^{-1}) in mixture (EC 1.45 dSm^{-1}), or in turn with non-saline water (EC 0.4 dSm^{-1}), a trend for yield decreases with increasing water and soil salinity was evident during 3 years in silt-loam non-saline and non-sodic (Chang et al., 1998). A significant average loss of about 1000 kg ha^{-1} of seed cotton from 2500 kg ha^{-1} was obtained with irrigation only with drainage water in that experiment. Use of saline water and seawater for cotton irrigation may be better feasible with genotypes derived from salt-tolerant selections of *Gossypium arboreum* L. that showed less sensitivity to salt stresses by saline irrigation (Ahmad and Abdullah, 1982). Furthermore, soils with an initial low salinity and exchangeable Na content may allow use of saline irrigation water with EC $>$ 7 dSm^{-1} without yield losses as compared with non-saline irrigation, at least in the short-term (Meiri et al., 1992).

Cycles of irrigation with discontinuous use of saline water may help to prevent saline build up in the soil over time. However, saline irrigation cycles may be planned in relation to the ionic composition of the irrigation water and to the soil type in order to minimize water use, especially in the presence of high B concentrations, which may require large amounts of non-saline water to be leached away. Otherwise, cotton stand establishment is reduced and yield decreases in particular in sensitive cultivars such as 'GC-510' (Shennan et al., 1995).

Use of sprinkler rather than surface irrigation may significantly reduce cotton yield. Due to evaporation losses when water is applied during the day, salts become concentrated in the water causing curling and necrosis especially in young plant leaves early in the growing season. However, night sprinkling may increase irrigation efficiency without reductions in yield (Bush and Turner, 1967). As compared to sprinkler irrigation, drip irrigation avoids any possible damage from leaf wetting and yield may increase for larger range of volumes of applied saline water instead of soon leveling, especially at high water salinity (Meiri et al., 1992). Drip irrigation may concentrate soil soluble salts between rows removing the excessive salt along rows with favorable effects on cotton yields. Favorable salt redistribution can be obtained with furrow irrigation that appeared effective for supporting cotton yields in saline conditions in Chile (Mamani et al., 1998). Uneven salt distribution created by localized irrigation systems requires careful application in order to prevent excessive addition of salts to the soil, especially when saline water is used. Salts accumulated between rows may not significantly decrease cotton yields only in the short term, unless seasonal rains are sufficient to periodically leach away excessive salt concentrations (Papadopoulos and Stylianou, 1988). Otherwise, redistribution of added salts by light precipitation may nullify beneficial temporary displacement of salts from the root zone (Mamani et al., 1998). The irrigation frequency may significantly interact with water and soil salinity in lowering cotton yields, the rate of reduction of cotton yield per unit increase in soluble salt concentration decreasing with increasing irrigation intervals (Soliman et al., 1976). Independently of the irrigation system, frequent irrigation is especially important when saline water is applied (Mamani et al., 1998). Scheduling irrigation in order to avoid water stress during sensitive stages such as flowering may affect quantity and quality of cotton lint more than the total applied volume (Heuer and Nadler, 1999). Length of irrigation intervals, the number of irrigation and total volume of applied water need to be concomitantly adjusted for maximizing yields (Mohamed et al., 1997). Water salinity interacts with irrigation volume in determining cotton yields. Increasing the irrigation volume above a threshold decreases yields even though the threshold volume is greater for more saline water. The rate of change of seed cotton yield per unit increase in salinity is affected by the amount of the irrigation water. Field trials have shown that increasing the amount of water applied may not fully compensate for the negative effect of salt concentration, suggesting that salinity may enhance aeration problems (Russo and Bakker, 1987). Excessive water applications in absence of proper drainage may raise the WT. Adequate drainage, is especially important when using saline water on clayey soils in order to improve cotton yields (Aich et al., 1997). As a function of drain density, especially in clay soils with saline ground water, the yield of cotton may vary from 1400 to 2500 kg ha^{-1} of raw cotton (Redzhepbaev, 1981).

Water table depths in shallow (< 120 cm) Mollic Torrerts were highly significantly related to EC and cotton yields in central Queensland, Australia, where soil salinity was a dominant soil factor in the variability of yields between 0 and 5600 kg ha^{-1} (Dowling et al., 1984). The depth of the WT interacts with texture, salinity and sodicity in determining cotton yield. Lower cotton yields at similar EC values were recorded in the presence of shallow ground water in the Nile Delta (Habib et al., 1993). Shallow WTs may affect cotton fiber quality, in particular decreasing fiber length uniformity and strength (Mohamed et al., 1997). Excess water due to high WTs depresses yields, whereas a WT at some depth (e.g., 2 m) can supply important fractions of the total water used by cotton in dry years. In addition, salinity in the capillary fringe above the WT limit the WT use fraction that is directly related to lint cotton yields. Experiments at the Soil Salinity Laboratory of Alexandria, in Egypt indicated that the WT must be kept deeper than 1 m for high cotton yields in Vertic Torrifluvents of clay loam texture (Mohamed et al., 1997). N fertilization tends to increase yield on saline soils even if the excess salts may affect plant root functionality (Mamani et al., 1998). Higher yield reductions per unit increase of EC and lower threshold salinity for yield reduction were observed in coarse-textured as compared to fine-textured soils (Habib et al., 1993).

The best sampling depth for testing soil salinity in relation to cotton yield is not clearly defined, as shown by contrasting results from EC measurements in soils of different texture and with WT at different depths. As compared to Acala (*Gossypium hirstum* L.) cotton cultivars, Pima (*Gossypium barbadense* L.) cultivars may show less salt-tolerance especially when reduced length of the growing season inhibit late fruit maturation and enhances the sensitivity of long-season varieties (Munk and Roberts, 1995).

Sugarcane (Saccharum officinarum L.*)*

Sugarcane is a major crop grown in areas subjected to soil salinization, and a considerable amount of literature exists with regards to its response to salinity (Table 4). Sugarcane has been considered highly salt-tolerant together with sugar beet (*Beta vulgaris*), barley and cotton (Shannon and Noble, 1990). Nevertheless, salinity, salinization and sodication, together with nutrient deficiencies, irrigation water and water quality, high

TABLE 4. Sugarcane yield reductions as a function of different soil salinity and sodicity (slopes of the linear regression, significant at $P < 0.05$).

Reference	Δ Cane yield	Δ Salinity or sodicity	Yield range ($Mg\ ha^{-1}$)	Salinity or sodicity range
Fogliata & Aso (1965)	−12 to −31 g/plant	1 ESP	5-150	1-60 ESP
Fogliata & Aso (1965)	−40 to −75 g/plant	1 dSm^{-1}	5-150	0.3-22 dSm^{-1}
Shuji & Sund (1967)	−0.11 $Mg\ ha^{-1}$	1 dSm^{-1}	10-120	1-9 dSm^{-1}
Mehrad 1969	−5.7 $Mg\ ha^{-1}$	1 dSm^{-1}	50-150	0.5-7 dSm^{-1}
Spalding (1983)	−1.5 $Mg\ ha^{-1}$	1 ESP	0-100	< 10->70 ESP
Hernandez et al. (1986)	−25.1 $Mg\ ha^{-1}$	1% soluble salts	50-30	0.1-0.7%
Farag et al. (1993)	−5.8 $Mg\ ha^{-1}$	Na^+ cmole kg^{-1}	130-70	0.7-9 cmole kg^{-1}
Zerega et al. (1995)	−4.8 $Mg\ ha^{-1}$	1 dSm^{-1}	0-109	7-22 dSm^{-1}
Zerega et al. (1995)	−24.7 $Mg\ ha^{-1}$	1 dSm^{-1}	0-87	$dS\ m^{-1}$
Nelson et al. (1998)	−2.4 $Mg\ ha^{-1}$	1 ESP	0-200	0.5-80 ESP

WT and poor drainage, stand out among the limiting factors of sugarcane production. Growing sugarcane on unsuitable soils is possibly the major limiting factor in cane culture worldwide (Rozeff, 1999). Many sugarcane fields have been abandoned as a consequence of increased soil salinity contributing to non-economical yields, especially where land and labor costs are high, as in Puerto Rico and Hawaii in the USA (Schwartz, 1995).

Salt-tolerance of sugarcane depends to a large extent on the ionic composition of the soil. Sugarcane can tolerate soil salinity up to 6 dSm^{-1} and still produce > 100 $Mg\ ha^{-1}$ of cane, when the dominant salt in the soil is $CaSO_4$ (Zerega and Hernandez, 1997). Francois and Maas (1999) reported an increase of 1-3 dSm^{-1} of critical salinity values for gypsum containing soils. The soluble fraction of gypsum interferes with the measurement of EC due to more soluble salts. On the other hand, crops tend to be more tolerant to salinity in saline gypsiferous soils, which are easier to manage, as shown for salt-affected gypsiferous soils of the Middle Euphrates Floodplain in Syria successfully reclaimed and cropped with irrigation with groundwater saturated with gypsum (Florea and Al-Joumaa, 1998). In the presence of Na and/or chloride growth and yield of sugarcane may decrease if the EC exceeds only 2 dSm^{-1} (Bosshart, 1981) or less at 1.6 dSm^{-1} (Barreto and Valdivia, 1979). The critical value for yield reductions of 1.7 dSm^{-1} indicated by Francois and Maas (1999) is close to 2. In Khuzestan (Iran) cane yield was reduced from > 100 Mg ha^{-1} of cane to < 50 Mg ha^{-1} with EC increasing from < 2 to > 5 dSm^{-1} (Shuji and Sund, 1967; Yield Mg ha^{-1} = 114.7 − 12.3 EC dSm^{-1}, R^2 = 0.87). There is a high proportion of salt-affected soils in the Johar area of Somalia. Increasing soil salinity to > 6-8 dSm^{-1} leads to the abandonment of sugarcane production, as shown by over 10,000 ha of Vertisols affected by secondary salinization in central Somalia (Falciai and Bruno, 1982). At EC > 4-5 dSm^{-1} and ESP > 10% sugarcane growth appeared usually impaired in Natal, and plants may not survive (Von der Meden, 1966).

In Queensland, in clay loams and clay soils, cane yield was reduced almost 200 Mg ha^{-1} per unit increase of EC (1:5) in conditions where yields varied between 252 and 1 Mg ha^{-1} with corresponding EC (1:5) from 0.5 to 0.9 dSm^{-1} (Nelson and Ham, 2000). In Vertisols in Cuba, yield of sugarcane was linearly related to the soil soluble salt content, with an average loss of about 25 Mg ha^{-1} of cane for every 1% increase in concentration of soluble salts (Hernandez et al., 1986; Yield Mg ha^{-1} = 43.7 − 25.1 soluble salt%, R^2 = 0.70). Continuation of sugarcane culture on Cuban salinized soils did not appear economical because yields were reduced to < 32 Mg ha^{-1} of cane by salinity. In saline-sodic soils in Lara (Venezuela) variation in EC explained 63-79% of the variability in yields of various varieties tested for values of EC (1:5) ranging from 1.5 to 22 dSm^{-1} (Zerega et al., 1995).

The harmful effect of Na can mask the relationship between soil salinity and cane yield especially at low salinity levels and in the presence of Na_2SO_4, which may be more deleterious than those of NaCl on sugarcane yield. In Maharashtra (India) cane yield was reduced from 120 to 80-85 Mg ha^{-1} with EC rising from 1.1 to 1.8 dSm^{-1}, but to 40-45 Mg ha^{-1} in case of higher alkalinity for the same EC range (Joshi and Naik, 1977; Yield Mg ha^{-1} = 123.9 − 22.9 EC dSm^{-1}, R^2 = 0.67). The exchangeable Na content in the soil explained about 74% of the variability in yield of sugarcane in soils with texture ranging from sand to clay (Farag et al., 1993; Y Mg ha^{-1} = 121.1 − 5.8 Na c mole kg^{-1}, R^2 = 0.74). The linear relation between soil exchangeable Na and sugarcane yield appeared very highly significant in Egyptian soils with similar EC, < 1 dSm^{-1} (Farag et al., 1993; Y Mg ha^{-1} = 121.1 − 5.8 Na C mole kg^{-1}, R^2 = 0.7). An average decrease of 2.5 Mg ha^{-1} of cane yield per 1% increase in ESP was reported in the Burdekin district in Queensland (Nelson and Ham, 1998; 2000). Yield reduction caused by excessive exchangeable Na^+ can be expected for ESP >10 and no sugarcane production can be expected at ESP > 45 (Valdivia, 1981).

In general, coefficients of determination (R^2) calculated for the significant and negative linear regression between cane yield and salinity or sodicity in a variety of environmental conditions and with diverse cultivars appeared around 70%. Non-linear models usually were not able to explain more variability of yield in terms of soil salinity (Mesa et al., 1979).

In the estimates of yield losses of sugarcane, it is necessary to consider different responses of the seed crop and of the ratoons in following years because the reductions in yield is more in not properly managed ratoon crops in salt-affected soils. Zerega et al. (1995) calculated different slopes and intercepts to quantify the linear relationship between EC and yield of cane in the seed plant and in ratoons. An average decrease of 25 Mg ha^{-1} of ratoons was observed per 1 dSm^{-1} increase of soil EC, whereas the reduction in seed plant yield was about 5 Mg ha^{-1}. The collapse of yield occurring in ratoon crops due to the soil sodicity may cause early abandonment of sugarcane culture even when only sodic spots affect a field and seed cropping is still feasible (Spalding, 1983).

Germination and emergence are not particularly sensitive stages, and are regular in saline soils with EC up to 5 dSm^{-1} (Valdivia and Pinna, 1977). At about 10 dSm^{-1} plant establishment can be 50% reduced in saline non-sodic soils. Salinity and sodicity adversely affect number, mass and length of canes resulting in highly significant linear decreases in yield, and variability can be explained for most part in terms of soil EC and ESP ($R^2 = 0.89$ for 'CP 36-14' in Argentina; Fogliata and Aso, 1965).

Soil salinity limits sugarcane response to high levels of N fertilization, but significant increases in yield were recorded for additions of N up to 180 kg ha^{-1} in soils with EC between 2 and 8 dSm^{-1} (Valdivia, 1981). Irrigation of sugarcane with medium saline water may not reduce sugarcane yields if the water is non-sodic and proper drainage is provided (Tavárez-Rodríguez, 1975).

Sugarcane is very sensitive to water logging and to the presence of high WTs. Experiments in Rhodesia with WTs at depths varying from 25 cm to 125 cm suggested that the WT should be at least 75 cm deep in loamy sands to prevent reductions in cane yield (Gosnell, 1973). In loamy Entisols of Northern Peru sugarcane was salt-tolerant when the WT was at 80-110 cm deep, giving good yields at 6-8 dSm^{-1}. However, for deeper WT in similar $CaSO_4$-rich soils the critical salinity for yield reductions was 2 dSm^{-1} (Valdivia, 1980). In Egypt, a depth of WT at 80 cm decreased cane yields to an average of 88 Mg ha^{-1} as compared to the average of 102 Mg ha^{-1} recorded with a WT at 150 cm depth (Farag et al., 1993). In Natal, South Africa, accumulation of excess salt impairing sugarcane yields was constantly observed with WTs shallower than 1-m depth in heavy saline soils (von der Meden, 1966). In the Dominican Republic, best sugarcane performances were recorded where the WT was deeper than 2 m (Tavárez-Rodríguez, 1975). Increase of Na concentration above the WT, and depletion of SOM and nutrients usually occur concurrently with the increase of soil salinity above the WT. All these factors are likely to contribute to yield losses up to 185 Mg ha^{-1} (Gosnell, 1973). Further experiments in different conditions are needed to distinguish the effect of high salt concentrations caused by high WT (Bosshart, 1981). The rooting depth in relation to the extent of capillary rise in soils of different texture and interactions with the ionic composition of the soil solution are to be taken into account. In Vertisols (60-65% clay), a decrease in cane yield from about 100 to 60 Mg ha^{-1} was observed in absence of drainage in fields where the EC was only 1 dSm^{-1} higher than in drained fields in Somalia (Falciai and Bruno, 1982). The WT depth did not limit sugarcane yields when proper drainage is installed (Mehrad, 1969; Yield Mg $ha^{-1} = 140.1 - 5.7$ EC dSm^{-1}, $R^2 = 0.16$, $P < 0.007$). Measurements of soil properties 4 years after drainage implementation have shown that drainage alone without addition of chemical amendments (such as sulphur or gypsum) may lower soil EC, pH and exchangeable Na below critical values for sugar cane (Experimental Station of the South African Sugar Association, 1975). Fluctuations in the WT depth are most common under field conditions. Following variations in WT depth, salt accumulation depth, and at the same time, soil water availability and aeration change and interact in determining sugarcane performance. The rise of the WT can mobilize and bring it to the topsoil salt deposited below, extending the area affected by salinization.

The depth where maximum salt concentration is found in the soil seems critical to identify a clear relationship between soil salinity and yield of sugarcane. It was reported that Na in the top 0-25 cm of soil was not enough to predict cane yield losses and ESP must also be determined at 25-50 cm depth (Spalding, 1983). Similarly, the EC measured at 0-60 cm depth was better correlated with sugarcane establishment in saline soils than the EC at 0-30 cm layer where germination and emergence occur (Valdivia and Pinna, 1977). Greater variability in the salt distribution close to the surface may support measurements taken at some depth, or maybe the top 45-50 cm, as suggested from field sampling in Natal (Von der Meden, 1966). Similar results were obtained in cane fields of Taiwan, where 40-60 cm sampling depth was suggested for salinity measurements (Wang and Hsu, 1952). The time of soil salinity measurement in relation to the crop stage is also important. Usually soil salinity is measured at harvest, or repeatedly monitored during the growing season. In Iranian fields at Haft Tappeh, soil EC measured before planting was explained only 16% of the variability in sugarcane yield of the seed crops ($P \leq 0.007$, $n = 38$) because subsequent variations of salinity may have weaken the relationship (Mehrad, 1969). For adequate stand establishment in Taiwan, the surface soil must contain < 0.35% soluble salts at the end of the dry season or < 0.18% soluble salts at 40-60 cm depth during the rainy season. After plant establishment, soil salinity tests at about 50 cm depth is better because at some depth salinity fluctuations are less pronounced and because cane roots develop deep (Wang and Hsu, 1952).

Interactions between soil type and salinity in terms of their affect on cane yield are not evident. Sugarcane tends to yield better on loamy soils than on sandy or clayey soils, without apparent relation to salinity or sodicity (Farag et al., 1993). Mesa et al. (1979) proposed different limits for yield reductions by soluble salts in soils of different textures in Cuba. These authors indicated that the level of excessive salinity increases from sandy to loamy to clayey soils (0.15, 0.19 and 0.38% soluble salts, respectively). In heavy soils (> 70% clay) cane yield decreased from 76 Mg ha^{-1} at soluble salt concentrations of < 0.19% to 12 Mg ha^{-1} at soluble salt concentrations of > 0.28%, becoming non-economical sugarcane culture at > 0.38% soluble salts. On the contrary, the data from Australian Bureau of Sugar Experiment Stations indicate higher thresholds for yield reductions in soils of finer textures with severe restriction to sugarcane growth on clay soils at EC 1:5 > 0.97 dSm^{-1} and at > 0.42 dSm^{-1} on sandy soils (Chapman, 1995). Presence of SOM may alleviate the negative effects of salinity by improving soil physical properties. The ameliorative effects of SOM were demonstrated by repeated applications of sugar industrial residues (mill mud) in the Burdekin district in Queensland. Application of biosolids increased cane yield of seed crops from 50 to 150 Mg ha^{-1} (yields similar to non saline soils) although the EC did not significantly decrease and ratoons crops were still susceptible (Bureau of Sugar Experiment Stations, 1994).

In addition to change in yield, there are also changes in quality of sugarcane in saline and sodic soils. Due to soil salinity, the sucrose percentage may decrease even more markedly than the cane yield, especially in ratoon crops (e.g., in the second ratoon crop about 2% sucrose loss for an increase of EC from 3 to 6 dSm^{-1} at 0-15 cm depth, Gosnell, 1973). In the seed crop, the quality effect may not be so evident but the trends for decreased cane juice quality was confirmed (Mehrad, 1969). Further reductions in net sugar yield occur during the process of extraction because mineral ions in the cane juice tend to increase in saline soils, decreasing the amount of recoverable sugar (Lingle et al., 2000).

Francois and Maas (1999) rated sugarcane as moderately sensitive to salinity with non-significant differences in performance of different cultivars at low salt concentrations. But experiments in field conditions showed that some varieties are particularly sensitive to salinity. The sensitivity to excess salt of some sugarcane cultivars such as 'Co 740' can be related to its incapability of proline accumulation for osmotic adjustment, while photosynthesis and protein synthesis are hindered by increasing salinity (Joshi and Naik, 1977). Different responses to sodicity of different sugarcane varieties were shown on a Na-affected clay loams (Typic Ustochrept) in India (Dang et al., 1998). Both amount of canes and sucrose percentage in the juice of all cultivars were reduced by an ESP increase from 14.4 to 23.5 (EC increasing from 0.35 to 0.60 dSm^{-1}). The effects were more pronounced in early than mid and late maturing genotypes. Among 10 cultivars tested, the early-maturing 'CoH 56' produced the highest yields (11.5 Mg ha^{-1} of recoverable sugar) on non-saline soil and almost 2 Mg ha^{-1} of recoverable sugar less on sodic soil.

Varietal differences in the response to salinity and to sodicity have been known and studied for long. Low yielding local varieties, such as 'Pundia' in India, were the only sugarcane cultivars grown in salt-affected soils (Talati, 1947). However, new cultivars have been tested for salt-tolerance since 1926. Experiments carried out since 1937-38 on saline (EC > 4 dSm^{-1}) soils and on sodic (ESP > 15) soils showed potential improvement of yields by introducing new selections, such as 'Co 290'. 'Co 290' gave 15.3 Mg ha^{-1} of cane on a saline soil and 10.8 Mg ha^{-1} of cane on a sodic soil where 'Pundia' was producing, respectively, 6.1 and 3.1 Mg ha^{-1}. Other cultivars, such as 'POJ 2878', were already known to stand soil sodicity very well, but not concentrations of soluble salts > 0.5%. Cane yields in southern India during the 1930's were about 10% of what these are during the first decade of the 21st century. In Argentina, different Na and salt-tolerance of different varieties was shown in sugarcane plantations of the Tucuman region where 'CP 36-14' showed more sensitivity to sodicity and to salinity than 'CP 34-120' (Fogliata and Aso, 1965). Recently, tissue and cell culture techniques have been suggested for selecting salt-tolerant varieties able to increase sugarcane yield on saline soils of Taiwan (Liu and Chen, 1981). The genetic improvement of sugarcane in Jamaica has been focused on the tolerance to soil salinity, which constitutes a major limitation to high yields in the island (Feldmann et al., 2001). Biotechnology has been applied to sugarcane, transforming sugarcane varieties by gene insertion, and transformed lines have been evaluated in field trials in Australia, South Africa, and the US

(Moore, 1999). However, transgenic plants have been developed mainly for herbicide tolerance and for resistance to insects and diseases. Although good potential exists for engineering sugarcane metabolic pathways in order to improve crop performance in saline and sodic soils, the progress of molecular genetics of sugarcane is slowed because sugarcane is a high polyploid with a large complex genome (Moore, 1999).

The importance of cultivar differences on yield losses in salt-affected soils was most evident in field trials for screening among nine cultivars conducted on Ovalles clay (fine, mixed, isohyperthermic, saline-sodic Aquic Eutropept) in Venezuela (Zerega et al., 1995). The salt-tolerant 'PR 980', 'My 5514' and 'PR 692176' produced on the average 90 Mg ha^{-1} of cane on plots with EC (1:5) ranging from 1.5 to 7.5 dSm^{-1}, where other cultivars failed. Seed plants of 'My 5514' produced 63 Mg ha^{-1} of cane at EC (1:5) around 12.5 dSm^{-1}. 'PR 980' can normally grow on soils with 4 dSm^{-1}, and was widely adopted on saline soils in the Dominican Republic, with satisfactory yields. Other salt-tolerant sugarcane cultivars have been released by the Experimental Station of Aiea, Hawaii.

Besides the choice of salt-tolerant varieties, all management practices that enhance the productivity of sugarcane may contribute to lower the relationship between soil salinity and yield reductions. In particular, careful soil preparation, frequent application of fertilizers and amendments, sanitary and weed control, crop rejuvenation (increasing the proportion of seed crops vs. ratoons), frequent rational irrigation, and implementation of effective drainage systems (Tavárez-Rodríguez, 1975).

CONCLUSIONS

There are numerous options for sustainable management of salt-affected soils (Table 5). The method of irrigation affects the salt distribution, and the rooting pattern of the crop (Shannon and Noble, 1990). Use of saline irrigation may be favored by developmental changes of crop salt-tolerance if accumulation of salts during the growing season is accompanied by decreased sensitivity of crops to the salt concentration. Crop yield response to soil salinity depends on soil water regime, which is modified by irrigation amounts, frequency and salinity of irrigation water. Therefore, waters with a wide range of salinity may be successfully used for crop irrigation provided that appropriate water quantities are applied in relation to local soil, plant and climatic conditions.

In addition to management, there is also a vast potential of improved salt-tolerance of species and cultivars to:

- extend the choice of crops that can grow at each soil salinity level,
- allow irrigation using more saline water, and
- increase SOM and improve soil structure.

Consequently, salt-tolerant plants can be cropped while land reclamation is still in process, especially if care is taken to match the plant cycle to the seasonal changes of soil salinity in the root zone. Appropriate seeding and/or transplanting techniques may be applied to attain sufficient stand density. Seed broadcasting is not advisable because it hinders consequent tillage operations. Afforestation may assist in establishing a proper water balance. Planting forests on coastal areas can limit intrusion of saline seawater. Trees can be used to create wind belts and limit water losses by evaporation. In addition, trees and other deep-rooted species can extract deep groundwater and control the level of the WT. High value crops allow implementation of intensive and costly amendments or irrigation-drainage systems. Perennial species are particularly favorable because they assure a continuous vegetative soil cover. Deep-rooted, perennial species can escape early sensitive stages of development and surface salt-concentration. Continuous vegetative cover limits evaporation losses. Similarly minimizing fallow periods in favor of cropping on salt-affected lands is useful for reducing water evaporation and deep percolation, and increasing the organic matter content of the soil.

TABLE 5. Management practices for agricultural use of salt-affected soils.

Type	Management practices
Hydraulic	Irrigation (leaching, method efficiency) Drainage (disposal, method efficiency) Mulching
Mechanical	Embankments, dykes Land shaping (leveling, ridging) Tillage (deep, chiseling, plowing, seedbed preparation, cultivation, no-tillage)
Amendment	Gypsum, lime, sulfur Animal & green manure, crop residues
Cropping system	Salt-tolerance (species, cultivars) Cycle (duration, timing, seed rates, transplanting) System (perennial & deep rooted crops, afforestation, continuous cropping)

REFERENCES

Abdel-Ghany, M.B., M.S. Abdel-Dayem, and M.R. Nasralla. 1996. Impact of drainage on groundwater table soil salinity and crop yield. Pp. 706-717. In *Proceedings of 6th Drainage Workshop on Drainage and the Environment.*

Abraham, L., and J. Boskai. 1971. The utilization of solonetz soils in Hungary. In I. Szabolcs (ed), *European solonetz soils and their reclamation*. Akademiei Kiado, Budapest, Hungary.

Abrol, I.P., and D.R. Bhumbla. 1979. Crop responses to differential by gypsum application in a highly sodic soil and the tolerance of several crops to exchangeable sodium under field conditions. *Soil Science* 127:79-85.

Ahmad, R., and Z. Abdulla. 1982. Biomass production of food and fiber crops using highly saline water under desert conditions. Pp. 149-163. In *Biosaline Research*; *Proceedings from the 2nd International Workshop on Biosaline Research 1980.* La Paz, Mexico.

Aich, A.C., A.H.M. Ahmed, and R. Mandal. 1997. Economic feasibility of bamboo subsurface drainage in coastal saline soils of Bangladesh. *International Journal of Tropical Agriculture* 15:157-164.

Al-Abdulsalam, M.A., O.A. Al-Tahir, A.A. Al-Jasim, and H.O. Burhan. 1993. Wheat growth as influenced by the interaction of drainage water and nitrogen fertilization. *Expl. Agriculture* 29:195-200.

Asch, F., M. Dingkuhn, C. Wittstock, and K. Doerffling. 1999. Sodium and potassium uptake of rice panicles as affected by salinity and season in relation to yield and yield components. *Plant and Soil* 207:133-145.

Asch, F., M. Dingkuhn, K. Dorffling, and K. Miezan. 2000. Leaf K/Na ratio predicts salinity induced yield loss in irrigate rice. *Euphytica* 113:109-118.

Asch, F., and M.C.S. Wopereis. 2001. Responses of field-grown irrigated rice cultivars to varying levels of flood water salinity in a semi-arid environment. *Field Crops Research* 70:127-137.

Ashraf, M., and S. Ahmad. 1999. Exploitation of intra-specific genetic variation for improvement of salt (NaCl) tolerance in upland cotton (*Gossypium hirsutum* L.). *Hereditas* 131:253-256.

Ayers, R.S., and D.W. Westcott. 1989. Water quality for agriculture. *FAO Irrigation and Drainage Paper* 29, Rev. 1. FAO, Rome, Italy.

Bajwa, M.S., and A.S. Josan. 1989. Effect of gypsum and sodic water irrigation on soil and crop yields in a rice-wheat rotation. *Agricultural Water Management* 16:53-61.

Bajwa, M.S., A.S. Josan, and O.P. Choudary. 1993. Effect of frequency of sodic and saline-sodic irrigations and gypsum on the buildup of sodium in soil and crop yields. *Irrigation Science* 14:21-26.

Ball, M.C., and M.A. Sobrado. 1999. Ecophysiology of mangroves: Challenges in linking physiological processes with patterns in forest structure. Pp. 331-346. In M. C. Press, J. D. Scholes, and M. G. Barker (eds.) *Physiological Plant Ecology: The 39th Symposium of the British Ecological Society*. University of York, 7-9 September 1998. Blackwell Science, Oxford, Malden, MA, USA.

Barreto, R.J., and V.S. Valdivia. 1979. Effect of salinity on sugarcane yield and on physico-chemical characteristics of soil. *Saccharum* 7(2):81-102.

Bastiaanssen, W.G.M., D.J. Molden, and A.A.M.F.R. Thiruvengadachari et al. 1999. Remote sensing and hydrologic models for performance assessment in sirsa irrigation circle, India. *International Water Management Institute* 27:1-29.

Bernstein, L. 1964. Salt tolerance of plants. *USDA Information Bull*. 283. Washington, DC, USA.

Bernstein, L. 1974. Crop growth and salinity. Pp. 39-54. In J. van Schilfgaarde (ed.) *Drainage for Agriculture, Agronomy*, 17. ASA, Madison, WI, USA.

Bockheim, J.G. 1997. Properties and classification of cold desert soils from Antarctica. *Soil Sci. Soc. Am*. 61(1):224-231.

Bockheim, J.G., and A.N. Gennadiyev. 2000. The role of soil-forming processes in the definition of taxa in Soil Taxonomy and the World Soil Reference Base. *Geoderma* 95:53-72.

Bohn, H.L., B.L. McNeal, and G.A. O'Connor. 1985. *Soil Chemistry*. John Wiley & Sons, New York, NY, USA.

Bole, J.B., and S.A. Wells. 1979. Dryland soil salinity: Effect on the yield and yield components of 6-row barley, 2-row barley, wheat, and oats. *Can J. Soil Sci*. 59:11-17.

Bosshart, R.P. 1981. Changes in soil salinity and sodicity at HC&S company and pioneer mill company, Ltd. Pp. 19-20. In D.J. Meive and M.K. Carlson (eds.) *Annual Report (1980) of Sugar Planters Association*. Sugar Planters Association, Ailea, Hawaii.

Bureau of Sugar Experiment Stations.1994. Slating effects reduced by mill mud. *BSES Bulletin* 46:10-11.

Busch, C.D., and F. Turner, Jr. 1967. Sprinkler irrigation with high salt content water. *Trans. Am. Soc. Agric. Eng*. 10:494.

Cassanova, D., J. Goudriaan, J. Bouma, and G.F. Epema. 1999. Yield gap analysis in relation to soil properties in direct-seeded flooded rice. *Geoderma* 91:191-216.

Ceuppens, J., and M.C.S. Wopereis. 1999. Impact of non-drained irrigated rice cropping on soil salinization in the Senegal River Delta. *Geoderma* 92:125-140.

Chang, C., T.G. Sommerfeldt, G.B. Schalje, and C.J. Palmer. 1986. Effect of subsoiling on wheat yield and salt distribution of a solonetzic soil. *Can. J. of Soil Sci*. 66:437-443.

Chang, M.H., M. Sheikh, and A.M. Leghart. 1998. Conjuctive use of canal water and saline drainage effluent for crop production. *J. Drainage and Water Management* 2(2):29-34.

Chapman, F. 1995. Drought causes salt problems. *BSES Bulletin* 50:23.

Choudhary, O.P., M.S. Bajwa, and A.S. Josan 1996. Tolerance of wheat and triticale to sodicity. *Crop Improvement* 23:238-246.

Choudhary, O.P., A.S. Josan, and M.S. Bajwa. 2001. Yield and fiber quality of cotton cultivars as affected by the build up of sodium in the soils with sustained sodic irrigations under semi-arid conditions. *Agricultural Water Management* 49:1-9.

Dang, Y.P., A.S. Mehlea, R. Chhabra, and S. Kumar. 1998. Sodicity Induced Yield Losses and Changes in Mineral Concentration of Sugarcane Genotypes A123-A135. Pp. 123-134. In *Sugar Technologists Association of India Convention*. New Dehli, Shimla India.

Datta, K.K., V.P. Sharma, and D.P. Sharma. 1998. Estimation of a production functions for wheat under saline conditions. *Agricultural Water Management* 36:85-94.

Dowling, A.J., D.F. Yule, and A.T. Lisle. 1984. The salinization of vertisols with shallow water tables in the Emerald Irrigation Area. *Reviews in Rural Science* 5:285-291.

Dregne, H.E., Z. Xiong, and S. Xiong. 1996. Soil salinity in China. *Desertification Control Bulletin* 28:28-33.

Driessen, P.M., and R. Dudal (eds.) 1991. *The Major Soils of the World*. Agricultural University Wageningen, Wageningen, Netherlands.

El Falaky, A.A., and A.A. Rady. 1993. Salt tolerance of rice and cotton crops grown in salt affected soils. *Tasks for Vegetation Science* 28:147-151.

El-Saidi, M.T. 1997. Salinity and its effect on growth, yield and some physiological processes of crop plants. Pp.111-127. In P.K. Jaiwal, R.P. Singh, and A. Gulati (eds.). *Strategies for Improving Salt Tolerance in Higher Plants.* Science Publ., Enfield, NH, USA.

Esenov, P.E., and K.R. Redjepbaev. 1999. The Reclamation of Saline Soils. Pp. 167-179. In A.G. Babaev (ed.) *Desert Problems and Desertification in Central Asia: The Researches of the Desert Institute.* Springer, New York, NY, USA.

Experimental Station of the South African Sugar Association. 1975. *Annual Report 1974-1975*. Experimental Station of the South African Sugar Association, Mount Edgecombe, Natal.

Falciai, M., and V. Bruno. 1982. Drainage trials for salinity control. *Rivista-di-Agricoltura-Subtropicale-e-Tropicale* 76:261-285.

FAO-AGL. 2000. *Global Network on Integrated Soil Management for Sustainable Use of Salt-Affected Soils*. FAO-AGL, Land and Plant Nutrition Management Service (http://www.fao.org/ag/AGL/agll/spush).

FAO-ISIRIC-ISSS. 1998. *World Reference Base for Soil Resources*. FAO, ISRIC and ISSS, Rome.

Farag, M.A., A.L. Allam, and D.Z. Sergany. 1993. Effect of agripractices, pedilogical and hydrologica factors on yield of sugarcane in Kom-Ombo, Aswan (Egypt). *Egypt. J. Agric. Res.* 71:241-257.

Feldmann, P., A. D'Hont, E. Guiderdoni. 2001. Sugarcane. Pp. 506-524. In Andre Charrier (ed) *Tropical Plant Breeding*. Science Publishers, Montpeiller, France.

Florea, N., and Kh. Al-Joumaa. 1998. Genesis and classification of gypsiferous soils of the Middle Euphrates Floodplain, Syria. *Geoderma* 87:67-85.

Flowers, T J., and A.R. Yeo. 1997. Breeding for salt resistance in plants. Pp. 247-264. In P. K. Jaiwal, R. P. Singh, and A. Gulati (eds.) *Strategies for Improving Salt Tolerance in Higher Plants.* Science Publ., Enfield, NH, USA.

Fogliata, F.A., and P.J. Aso. 1965. Efectos de la salinidad y sodio intercambiable del suelo en el crecimiento de la cana de azucar. *Revista Industrial y Agnicola de Tucumaan* 43(1):25-45.

Francois, L.E. 1982. Narrow row cotton under saline conditions. *Irrigation Science* 3:149-156.

Francois, L.E., C.M. Grieve, E.V. Maas, and S.M. Lesch. 1994. Time of salt stress affects growth and yield components of irrigated wheat. *Agronomy Journal* 86(1): 100-107.

Francois, L.E., and E.V. Maas. 1999. Crop Response and Management of Salt-Affected Soils. Pp. 169-201. In M. Pessarakli (ed.) *Hand Book of Plant and Crop Stress*. M. Dekker, New York, NY, USA.

Ghafoor, A., and M. Masood. 1999. Soils, tubewell water quality and wheat yields in different sections of a canal in the wheat cotton cropping zone. *Pakistan Journal of Agriculture Science* 36(1-2):6-9.

Gomes, E.M., H.R. Gheyl, and E.F. Silva. 2000. Improvement in chemical properties of a saline-sodic soil and rice yield under different treatments. *Revista Brasileira de Engenharia Agricola e Ambiental* 4(3):355-361.

Gosnell, J.M. 1973. Some effect of a water table level on the growth of sugar cane. *International Sugar Journal* 75:135-139.

Gupta, R.K., and I.P. Abrol. 1990. Salt-affected soils: Their reclamation and management for crop production. Pp. 225-284. In R. Lal and B.A. Stewart (eds.) *Soil Degradation*. Central Soil Salinity Research Institute, Karnal, Haryana, India.

Gupta, R.K., and I.P. Abrol. 1999. Salinity build-up and changes in the rice-wheat systems of the Indo-Gangetic Plains. *Expl. Agric*. 36:273-284.

Habib, I.M., E.A. El-Morsy, and A.A. Soaud. 1993. Cotton yield and fiber qualities in relation to field variability under soil salinity. *Egypt. J. Soil Sci*. 33(3):267-278.

Halvorson, A.D. 1990. Management of dryland saline seeps. Pp. 372-392. In K.K. Tanji (ed.) *Agricultural Salinity Assessment and Management*. ASCE manuals and reports No. 71, ASCE, New York, NY, USA.

Ham, G.J., A.Z. Cox, and G.G. McMahon. 1997. A review of sodic soils research in the Queensland sugar industry. Pp. 200-207. In *Proceedings of the Australian Society of Sugar Cane Technologists Conference*.

Hedlund, J., W. Evans, and J. Thomas. 1990. Project-level salinity management options. Pp. 393-409. In K. Tanji (ed.) *Agricultural Salinity Assessment and Management*. American Society of Civil Engineers, New York.

Hernandez, A., J.M. Torres-Font, A. Vanour, and A. Salazar. 1986. Dark plastic soils at the sugarcane area of the "Cristino Narango" mill (Cuba): 3. Salts contents and composition 3. *Ciencias de la Agricultura* (26):79-85.

Heuer, B., and A. Nadler. 1999. Physiological parameters, harvest index and yield of deficient irrigated cotton. *J. Crop Prod*. 2:229-239.

Hilgard, E.W. 1886. *Alkali Lands, Irrigation and Drainage in Their Mutual Relations*. University of California College of Agriculture Annual Report 1886, Sacramento, CA.

Huang, J., and S. Rozelle. 1995. Environmental stress and grain yields in China. *Amer. J. Ag. Econ*. 77(4):853-864.

Jeganathan, N., and A. Pain. 1982. Studies in salinity and sodicity on the rice growing in Grumosols of Murunkan. *Tropical Agriculturist* 138:117-124.

Joshi, G.V., and G.R. Naik. 1977. Salinity effect on growth and photosynthetic productivity in sugarcane var. Co. 740. *J. Indian Sugar* 27(6):329-332.

Kelman, W.M., and C.O. Qualset. 1991. Breeding for salinity-stressed environments: Recombinant inbred wheat lines under saline irrigation. *J. Crop Science* 31(6): 1436-1442.

Khosla, B.K., K.S. Dargan, I.P. Abrol, and D.R. Bhumbla. 1973. Effects of depth of mixing gypsum on soil properties and yield of barley, rice and wheat grown on a saline-sodic soil. *J. Indian Agric. Sci*. 43(11):1024-1031.

Kim, S., W. Yang, W. Choi, H. Park, M. Choi, N. Back, S. Kang, H. Shin, S. Cho, S. Kwon, and B. Ko. 1999. Effects of desalinization management on rice yield in seawater flooded field. *Korean J. Crop Sci.* 44:38-43.

Lal, K. 1996. Biochemical studies in relation to adaptability of sugarcane cultivars under saline soil. *Bharatiya Sugar* 22(5):23-26.

Lambers, H., F. Stuart Chapin III, and T.L. Pons. 1998. *Plant Physiological Ecology*. Springer-Verlaz, New York, NY, USA.

Läuchli, A., and E. Epstein. 1990. Plant responses to saline and sodic conditions. Pp. 1130-1137. In K. K. Tanji (ed.) *Agricultural Salinity Assessment and Management . ASCE Manuals and Reports No. 71, ASCE, New York, NY, USA.*

Lee, K.S., J.K. Nam, and H.T. Shin. 1999. Effective land preparation for wet seeding on a reclaimed saline soil in Korea. *International Rice Research Notes* 24(1):36.

Letey, J., K. Knapp, and K. Solomon. 1990. Crop-production functions under saline conditions. Pp. 305-326. In K. K. Tanji (ed.) *Agricultural Salinity Assessment and Management*. ASCE manuals and reports No. 71, ASCE, New York, NY, USA.

Lingle, S.E., R.P. Wiedenfeld, and J.E. Irvine. 2000. Sugarcane response to saline irrigation water. *J. Plant Nutr*. 23(4):469-486.

Liu, M.C., and W.H. Chen. 1981. Sugarcane breeding by the use of tissue and cell culture techniques. Pp. 189-199. *Proceedings of a Symposium on Plant Breeding*. Taiwan Agri. Research Institute.

Longnecker, D.E. 1973. The influence of soil salinity upon fruiting and shedding, boll characteristics, fiber quality, and yields of two cotton species. *Soil Sci*. 115: 294-308.

Maas, E.V., and G.J. Hoffman. 1977. Crop salt tolerance–Current assessment. *J. Irrigation Drainage* 103:115-134.

Maas, E.V., and J.A. Poss. 1989. Salt sensitivity of wheat at various growth stages. *Irrigation Science* 10:29-40.

Maas, E.V., S.M. Lesch, L.E. Francois, and C.M. Grieve. 1996. Contribution of individual culms to yield of salt stressed wheat. *Crop Sci*. 36(1):142-149.

Mamani, O.R., E.E. Doussoulin, and G.H. Serri. 1998. Response of cotton (*Gossypiulm barbadense*) to nitrogen fertilizer, plant density and leaching water in the Lluta Valley. *Idesia* 15:49-58.

Mathew, E.K., R.K. Panda, and N. Madhusudan. 2000. Influence of subsurface drainage on crop production and soil quality in a low-lying acid sulphate soil. *Agricultural Water Management* 47:191-200.

Mehrad, B. 1969. Effects of soil salinity on sugarcane cultivation at Haft Tappeh Iran. *Interational Society of Sugar Cane Technologists, Congress*, *13th*, *1968*. 13:746-755.

Meiri, A. 1984. Plant response to salinity: Experimental methodology and application to the field. Pp. 284-297. In I. Shainberg and J. Shalhevet (eds.) *Soil Salinity Under Irrigation: Processes and Management*. Springer-Verlag, New York, NY, USA.

Meiri, A., H. Frenkel, and A. Mantell. 1992. Cotton response to water and salinity under sprinkler and drip irrigation. *Agron. J*. 84:44-50.

Mesa, A., O. Suarez, and M. Naranjo. 1979. Estudio sobre el efecto de la salinidad de un vertisuelo sobre los rendimentos de la cana de azucar. *Agrotencia de Cuba* 11(2):13-17.

Miller, M.R., P.L. Brown, and R.N. Donovan et al. 1981. Saline seep development and control in the North American Great Plains–hydrologic aspects. *Agric. Water Management* 4:115-141.

Mohamed, M.E.S., and E.H. Haddad, and E.A. Mashaly. 1997. Cotton yield and fiber quality in relation to soil water table and irrigation frequency. *Egyp. J. Soil Sci*. 37(2): 251-266.

Montoroi, J.P., J. Albergel, A. Bubos, M. Fall, S. Sall, A. Bernard, D. Brunet, G. Dubee, and P. Zante. 1993. *Rehabilitation of Rice Fields in the Acid Sulphate Soils of Lower Casamance, Senegal*. Pp. 195-203. International Inst. for Land Reclamation and Improvement, Wageningen, Netherlands.

Moore, P.H. 1999. Sugarcane improvement in the 21st century via biotechnology. *International Sugar Journal Worldwide Sugar Edition* 101:434-438.

Munk, D.S., and B. Roberts. 1995. Growth and development of pima and acala cotton on saline soils. Pp. 190-192. In *Proceedings from the Beltwide Cotton Conf*. National Cotton Council of America, Memphis, TN.

Murphy, H.F. 1934. The salt content of some soils near the salt plain in Alfaalfa County, Oklahoma, in relation to crop production. *J. Am. Soc. Agronomy* 26: 644-650.

Naresh, R.K., P.S. Minhas, A.K.I. Goyal, C.P.S. Chauhan, and R.K. Gupta. 1993. Conjunctive use of saline and non-saline water. II. Field comparisons of cyclic uses and mixing for wheat. *Agricultural Water Management* 23:139-148.

Nelson, P.N., and G.J. Ham. 2000. Exploring the response of sugar cane to sodic and saline conditions through natural variation in the field. *Field Crop Research* 66: 245-255.

Nelson, P., G. Ham, and D.M. Hogarth. 1998. Soil Sodicity: Its influence on cane yield in the Burdekin. Pp. 248-250. In *Australian Society of Sugar Cane Technologists Conference 1998.*

Nobel, P.S. 1999. *Physiochemical and Environmental Plant Physiology, 2nd Ed*. Academic Press, San Diego, CA, USA.

Obrejanu, G.R., and G.H. Sandu.,1971. *Amelioration of Solonets and Solonetsized Soils in the Socialist Republic of Romania*. Pp. 99-130.

Oldeman, L. R., R.T.A. Hakkeling, and W.G. Sombroek. 1991. *Second revised edition. World Map of the Status of Human-Induced Soil Degradation. An Explanatory Note*. Pp. 35. International Soil Reference and Information Center, Wageningen, The Netherlands.

Omielan, J.A., E. Epstein, and J. Dvorak. 1991. Salt tolerance and ionic relation of wheat as affected by individual chromosomes of salt-tolerant Lophopyrum elongatum. *Genome* 34(6):961-974.

Papadopoulos, I., and Y. Stylianou. 1988. Trickle irrigation of cotton with treated sewage effluent. *J. Environ. Quality* 17(4):574-580.

Pearce, A.D., C.R. Dillon, T.C. Keisling, and C.E. Wilson. 1999. Economic and agronomic effects of four tillage practices on rice produced on saline soils. *J. Prod. Agric*. 12(2):305-312.

Pearson, G.A. 1960. Tolerance of crops to exchangeable sodium. *Agric. Res*. 216:1-4.

Raikov, L. 1971. Reclamation of solonetz soils in Bulgaria. Pp. 35-47. In I. Szabolcs (ed.) *European Solonetz Soils and their Reclamation.* Akademiai Kiado, Budapest.

Rains, D.W., S. Goyal, R. Weyrauch, and A. Lauchli. 1987. Saline drainage water reuse in a cotton rotation system. *California Agriculture* 41(9-10):24-26.

Redzhepbaev, K. 1981. Meliorative state of irrigated land in Turkmenistan. Pp. 37-45. In *Problems of Desert Development.* Allerton Press, New York, NY, USA.

Rengasamy, P. 1998. Sodic Soils. Pp. 265-277. In R. Lal, W. H. Blum, C. Valentine, and B. A. Stewart (eds.) *Methods for Assessment of Soil Degradation.* CRC Press, Boca Raton, FL, USA.

Rengasamy, P., and K.A. Olsson. 1991. Sodicity and soil structure. *Aust. J. Soil Res*. 29:935-952.

Rhoades, J.D. 1990. Overview: Diagnosis of salinity problems and selection of control practices. Pp. 393-409. In K. Tanji (ed.) *Agricultural Salinity Assessment and Management*. American Society of Civil Engineers, New York.

Rhoades, J.D., S.L. Rawlins, and C.J. Phene. 1980. *Irrigation of Cotton with Saline Drainage Water*. ASCE, Portland, OR, USA.

Richards, R.A., C.W. Dennett, C.O. Qualset, E. Epstein, J.D. Norlyn, and M.D. Winslow. 1987. Variation in yield of grain and biomass in wheat, barley and triticale in a salt-affected field. *Field Crops Research* 15:277-287.

Ritzk, T.Y., and W.C. Normand. 1966. A field study of some effects of salinity on sugarcane. *The Sugar Bulletin* 44:154-155.

Rogel, J.A., R.O. Silla, N. Vela de Oro, and F.A. Ariza. 2001. The application of the FAO and US soil taxonomy systems to saline soils in relation to halophytic vegetation in SE Spain. *Catena* 45:73-84.

Rozeff, N. 1999. Limitations to cane and sugar production in the field. *Intl. Sugar J*. 101(120):450-452.

Russo, D., and D. Bakker. 1987. Crop water production function for sweet corn and cotton irrigated with saline waters. *J. Amer. Soil Sci. Soc*. 51(6):1554-1562.

Saeed, M. 1990. *Effect of Soil Salinity on Moisture Deficit and Yield of Irrigated Wheat*. Asian Institute of Technology, Thailand, Bangkok.

Sandu, G., and N. Mihaesou. 1989. Ameliorarea solurilor saline si alcalica si in Cimpia Romana. *Problema de agrofitotehnie tegretic a si aplicata*. 6(3):251-258.

Schneider, R.P., B.E. Johnson, and F. Sobolik. 1980. Saline seep management: Is continuous cropping an alternative? *North Dakota Farm Research* 37(5):29-31.

Schwartz, T.K. 1995. U.S. Sugar production in the 1990's. *Zuckerind*. 120(11): 982-984.

Shannon, M.C., and C.L. Noble. 1990. Genetic approaches for developing economic salt-tolerant crops. Pp. 161-185. In K.K. Tanji (ed.) *Agricultural Salinity Assessment and Management*. ASCE manuals and reports No. 71, ASCE, New York, NY, USA.

Sharma, D.P., and Kormal-Singh. 1998. Effect of subsurface drainage system on some physiochemical properties and wheat yield under waterlogged saline soil. *J. Indian Soc. Soil Sci*. 46(2):284-288.

Sharma, D.P., K.V.G.K. Rao, and K.N. Singh. 1994. Conjunctive use of saline and non-saline irrigation waters in semi arid regions. *Irrigation Sci*. 15:25-33.

Shennan, C., S.R. Grattan, D.M. May, C.J. Hillhouse, D.P. Schachtman, M. Wander, B. Robets, S. Afoya, R.G. Burau, C. McNeish, and L. Zelinski. 1995. Feasibility of cyclis reuse of saline drainage in a tomato-cotton rotation. *J. Environ. Quality* 24(3):476-486.

Shuji, K., and K.A. Sund. 1967. Drainage and salinity investigations at the Halft Tapeh sugar cane project, Iran. Pp. 90-95. *International Society of Sugar Cane Technologists*.

Singh, M., A.K. Bhattacharya, T.V.R. Nair, and A.K. Singh. 2000. Ammonium loses through subsurface drainage effluent from rice fields of coastal saline sodic clay soils. *Water, Air, and Soil Pollution* 127:1-14.

Singh, B., and P. Narain. 1980. Effect of the salinity of irrigation water on wheat yield and soil properties. *Indian J. Agric. Sci*. 50:422-427.

Soil Science Society of America (SSSA). 1997. *Glossary of Soil Science Terms*. P. 134. SSSA, Madison, WI.

Soil Survey Staff. 1998. *Keys to Soil Taxonomy*. Eighth Edition. USDA, Washington, DC.

Soil Survey Staff. 1999. *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*. P. 436. US Department of Agriculture.

Soliman, N.F., M.F. Soliman, I.M. Anter, and H.K. Bakhat. 1976. Effect of irrigation regime under saline conditions on growth and yields of cotton plant in Calcareous soil. *Agriculture Research Review* 54(4):91-96.

Somaani, L.L., and S.N. Saxena. 1981. Role of some sources of organic materials alone and in conjunction with inorganic amendments in reclamation of a typical calcareous saline-alkali soil of Rajasthan. I. Effects on soil physical properties and crop yield. *Agrochimica* 25(3-4):232-242.

Spalding, R.D. 1983. Sodic areas: Effect on can yields in the Central District. *BSES Bulletin* 1:20-21.

Szabolcs, I. 1998. Salt buildup as a factor of soil degradation. Pp. 253-264. In R. Lal, W. H. Blum, C. Valentine, and B. A. Stewart (eds.) *Methods for Assessment of Soil Degradation*. CRC Press, Boca Raton, FL, USA.

Talati, R.P. 1947. Field experiments on the reclamation of salt lands in Baramati of Bombay Deccan. *Indian J. Agric. Sci*. 17:153-174.

Tanji, K.K. 1990. The nature and extent of agricultural salinity problems. Pp. 1-17. In K. K. Tanji (ed.) *Agricultural Salinity Assessment and Management*. ASCE manuals and reports No. 71, ASCE, New York, NY, USA.

Tavárez-Rodriguez, G.A. 1975. Saline and sodic soils of Neyba Valle. *Revista de la Facultad de Ciencias Agronomicas y Veterinaria* 3:41-43.

Tiwari, K.N., G. Dev, D.N. Sharma, and U.V. Singh. 1998. Maximizing yield of a rice-wheat sequence in recently reclaimed saline sodic soils. *Better Crops Int*. 12(2):9-11.

US Salinity Laboratory Staff. 1954. *Diagnosis and Improvement of Saline and Alkali Soils*. P. 160. L.A. Richards (ed.) USDA, USA.

Valdivia, V.S. 1980. Effect of water table depth on critical sugarcane salt concentration level. *Agronomy* 1:209-219.

Valdivia, V.S. 1981. Advances de la investigacion realizada en el Peru sobre los efectos de la salinidad en la produccion de la cana de azucar. *Turrialba*. 31:237-244.

Valdivia, V.S., and C.J. Pinna. 1977. Effect of salinity on sugarcane sprouting. *Saccharum* 5:51-59.

Van den Berg, C. 1950. The influence of salt in the soil on the yield of agricultural crops. *Intl. Congress of Soil Sci.* 1:411-413.

Von der Meden, E.A. 1966. Notes on salinity limits for sugarcane in Natal. *Proceedings of the South African Sugar Tech. Assoc. Congress* 40:273-275.

Wang, S.C., and K.H. Hsu. 1952. Application of electrical conductivity measurement to the investigation of saline sugarcane soils in Taiwan. Pp. 61-63. In *Society of Soil Fertilizer Technologists of Taiwan*. Society of Soil Scientists and Fertilizer Tech. of Taiwan, Taipei, Taiwan.

Warrick R.A., C. Le Prevost, M.F. Meier, J. Oerlemans, and P.L. Woodworth. 1996. Changes in sea level. Pp. 263-405. In J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.) *Climate Change 1995.* Cambridge University Press, Cambridge, UK.

Wichelns, D., H. Richard, H. Gerald, and N. Daniel. 1990. Economic effects of long-term restrictions on water disposal. *Applied Agricultural Research* 5(1):48-55.

Wiegand, C.L., J.D. Rhoades, D.E. Escobar, and J.H. Everitt. 1994. Photographic and videographic observations for determining and mapping the response of cotton to soil salinity. *Remot-Sens-Environ*. 49(3):212-223.

Wijeratne, M. 1999. An FSR/E Application: Identification of Targets for Technology Generation and Transfer. *Der Tropeniandwirt, Beltrage zur tropiachen Landwirtschalt und Veteriniarmedizin* 8:196-203.

Wilson, C.E., T.C. Keisling, D.M. Miller, C.R. Dillon, A.D. Pearce, D.L. Frizzell, and P.A. Counce. 2000. Tillage influence on soluble salt movement in silt loam soils cropped to paddy rice. *SSSA* 64(5):1771-1776.

Worchester, B.X., L.J. Brun, and R.P. Schneider. 1979. Growth and development of saline seeps. *North Dakota Farm Research* 36(5):16-19.

World Commission on Environment and Development. 1987. *Our Common Future*. Oxford Univ. Press, Oxford.

Yamaguchi-Shinozaki, K., K. Shinozaki. 2001. Improving plant drought, salt and freezing tolerance by gene transfer of a single stress-inducible transcription factor. Pp. 176-181. In J.A. Goode and D. Chadwick (eds.) *Rice Biotechnology: Improving Yield, Stress Tolerance and Grain Quality.* Wiley, New York.

Zapata, F.J., M.S. Alejar, L.B. Torrizo, A.U. Novero, V.P. Singh, and D. Senadhira. 1991. Field performance of anther-culture-derived lines from F1 crosses of Indica rice under saline and nonsaline conditions. *Theor. Appl. Genet.* 83(1):6-11.

Zerega, L., and T. Hernandez. 1997. Influence of the chemical fertilization on the soil salinization and sugarcane crop. II. Medium term. *Cana de azucar*. 15(2):53-67.

Zerega, L.M., T. Hernandez, and J. Vallandares. 1995. Effect of three amendments on saline sodic soil used to grow nine sugarcane cultivars. *Cana de azucar*. 13(2): 51-64.

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